AEROSPACE VEHICLE SYSTEMS INSTITUTE

December 6, 2021

VIA ECFS

Ms. Marlene H. Dortch, Secretary
Federal Communications Commission
45 L Street, NE
Washington, DC 20554

Re: Written Ex Parte – *AVSI Project Report 76S2-REP-03*, GN Docket No. 18-122

Dear Ms. Dortch:

On behalf of the Aerospace Vehicle Systems Institute ("AVSI") project team, AVSI is pleased to provide the attached report "Derivation of Radar Altimeter Interference Tolerance Masks. Volume I: Introduction, Test Procedures, and Fundamental Test Results Effect of Out-of-Band Interference Signals on Radio Altimeters" to support the Commission's review of the findings of the report previously filed by RTCA, "Assessment of C-Band Mobile Telecommunications Interference on Low Range Radar Altimeter Operations", which demonstrated the risk for harmful interference to radar altimeters (RAs)[1] from new 5G emissions in the 3700-3980 MHz frequency band.[2] This is the first volume of a three volume report. The remainder of the report will be released sequentially, upon completion and release approval of each individual volume.[3]

AVSI has consistently supported earnest independent analysis of this data, subject to AVSI rules for protecting proprietary information, and this filing continues this support. Indeed, U.S. wireless industry representatives requested access to this data during a formal data exchange process established under a wireless industry hosted multi-stakeholder group (TWG-3) prior to release of the C-Band Order.[4] At the time, AVSI offered the possibility of access under an appropriate non-disclosure agreement (NDA).[5] However, AVSI received no request from wireless industry representatives to establish such an agreement until nearly a year after being so informed.

These previous requests highlight the need for clarity concerning the context and limitations of the data collected under the AFE 76s2 project, and contained in the attached report. AFE 76s2 was limited to black-box testing (i.e., testing a system without regard to its internal workings) of a limited number of RAs. The intent was to investigate the possibility of harmful interference from out-of-band emissions. It was not to perform testing to establish compliance with minimum performance standards (MPS) in various RF interference environments, and it was not directed at compatibility studies using data from the International Telecommunications Union

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[1] Radar altimeters are also commonly referred to as "radio altimeters."

[2] RTCA, Assessment of C-Band Mobile Telecommunications Interference on Low Range Radar Altimeter Operations, RTCA Paper No. 258-20/SC239-006 (rel. Sept. 18, 2020) ("RTCA MSG Report"), attached to Letter from Terry McVenes, RTCA, Inc., to Marlene Dortch, FCC, GN Docket No. 18-122 (filed Oct. 20, 2020).

[3] Due to ECFS file size limitations, the full Volume 1 report is posted in parts. The full integrated report can be obtained from AVSI by request.

[4] *Expanding Flexible Use in the 3.7-4.2 GHz Band*, Report and Order and Order Proposing Modification, 35 FCC Rcd 2343 (2020) ("C-Band Order").

[5] RTCA Report at 134.

– Radiocommunications (ITU-R) Recommendation ITU-R M.2059.[6] While these documents informed the testing under AFE 76s2, the black-box nature of the testing limits analysis to the readings on the standard output from the RA while subjecting the RA to interference at the standard input port. This method of testing incorporates all the internal signal chain within the RA, including front end filters, homodyne or heterodyne detection, and signal processing, without detailed knowledge of any of the internal features, and assesses the very same output an aircraft must use to determine correct altimeter readings. The only component of the transmit-receive-detect signal chain that was not incorporated in AVSI testing was the effect of antenna performance, although this was incorporated in subsequent analyses by RTCA.

AVSI has subsequently received several requests to access the data that led to the ITMs reported in the RTCA MSG Report. One such request has already been fulfilled under an NDA that defines the purpose of the data exchange and the specific terms governing the access to the data. In this case, Project Technology consisting of raw interference performance data were provided to the recipient with all identifying information removed, preventing traceability of this performance data to the specific altimeter models that were tested. The purpose of the exchange was to support an independent assessment of the findings of the RTCA MSG Report, including independent determination of the ITMs from the raw data, which is entirely possible using anonymized raw data.

Given the number of requests for access to AFE 76s2 Project Technology, the Project Participants have concluded that it would be most efficient to release this report in order to allow additional independent review of the data and methods employed by AVSI. This approach will follow the precedent established with the first agreement referenced above, namely to limit any release to anonymized data.

It is hoped that this release will be reciprocated in kind by the 5G community, as multiple requests for 5G power and other parameters are still outstanding in the Commission's public record.[7] Open collaboration of the relevant parties is both desired and necessary to resolve this critical issue in a way that is timely, accommodating of the Commission's plans for rolling out 5G, and consistent with continued aviation safety.

Respectfully submitted,

/s/ David Redman
Dr. David Redman – Aerospace Vehicle Systems Institute
On behalf of the AVSI AFE 76s2 project team

[6] Recommendation ITU-R M.2059, *Operational and Technical Characteristics and Protection Criteria of Radio Altimeters Utilizing the Band 4 200-4 400 MHz* (02/2014) (Rec. ITU-R M.2059).

[7] *See, e.g.,* Letter of The Aerospace Industries Association, Air Line Pilots Association, International, Aircraft Owners and Pilots Association, Airborne Public Safety Association, Airbus, Aircraft Electronics Association, Airlines for America, Aviation Spectrum Resources Inc., Boeing, Cargo Airline Association, Collins Aerospace, Experimental Aircraft Association, FreeFlight Systems, Garmin International, Inc., General Aviation Manufacturers Association, Helicopter, Association International, Honeywell International Inc., International Air Transport Association, National Air Carrier Association, National Business Aviation Association, and Regional Airline Association to Marlene H. Dortch, Secretary, FCC, GN Docket No. 18-122 (filed Nov 2, 2021).

AFE 76s2 Report

Derivation of Radar Altimeter Interference Tolerance Masks

Volume I: Introduction, Test Procedures, and Fundamental Test Results

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List of Acronyms

3GPP	3rd Generation Partnership Project
5G	Fifth generation technology standard for broadband cellular networks
ACP	Adjacent Channel Power
AFE	Authorization for Expenditure (for AVSI Projects)
AGL	Above Ground Level
ARINC	Aeronautical Radio, Incorporated
ASRI	Aviation Spectrum Resources Inc.
AUT	Altimeter Under Test
AVSI	Aerospace Vehicle Systems Institute
AWGN	Additive White Gaussian Noise
BPI	Background Proprietary Information
BPSK	Binary Phase-Shift Keying
BW	Bandwidth
CDF	Cumulative Distribution Function
CF	Center Frequency
DoD	U.S. Department of Defense
EUROCAE	European Organization for Civil Aviation Equipment
FAA	U.S. Federal Aviation Administration
FCC	U.S. Federal Communications Commission
FMCW	Frequency Modulated Continuous Wave
FSMP	ICAO Frequency Spectrum Management Panel
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ITM	Interference Tolerance Mask
ITU	International Telecommunications Union
ITU-R	International Telecommunications Union – Radiocommunications
JI-FRAI	Joint Interagency 5G Radar Altimeter Interference
ME	Mean Error
MPS	Minimum Performance Standard
NASA	U.S. National Aeronautics and Space Administration
NDA	Non-Disclosure Agreement
NCD	No Computed Data
NR-FR1-TM 1.1	5G NR Frequency Range 1 Test Model 1.1

OFDM	Orthogonal Frequency-Division Multiplexed
OOB	Out-of-Band
OOBI	Out-of-Band Interference
PEP	Peak Envelope Power
PMC	Project Management Committee
PSD	Power Spectral Density
PT	Project Technology
QPSK	Quadrature Phase-Shift Keying
RA	Radar Altimeter; also commonly referred to as Radio Altimeter
RBW	Resolution Bandwidth
RF	Radio Frequency
RTCA	RTCA, Inc. (formerly Radio Technical Commission for Aeronautics)
Rx	Receive or Receiver
SARPs	Standards and Recommended Practices
SCPI	Standard Commands for Programmable Instruments
SCS	Subcarrier Spacing
SQL	Structured Query Language
TSO	Technical Standard Order
Tx	Transmit or Transmitter
UC	Usage Category
UC1	Usage Category 1
UC2	Usage Category 2
UC3	Usage Category 3
USB	Universal Serial Bus
VCO	Voltage-Controlled Oscillator
VSG	Vector Signal Generator
WAIC	Wireless Avionics Intra-Communications
WCLS	Worst Case Landing Scenario

Executive Summary

The Aerospace Vehicle Systems Institute (AVSI) Project AFE 76s2 – *Out-of-band Interference with Radio Altimeters* tested nine commercial radar altimeter models for their sensitivity to fundamental emissions in the 3700 – 3980 MHz band and spurious emissions in the 4200 – 4400 MHz band from new flexible use (5G) signals as proposed (and ultimately authorized) by the Federal Communications Commission (FCC) in their March 2020 Report and Order. These tests resulted in a set of interference tolerance thresholds that were provided to RTCA, Inc. for use in their Special Committee SC-239 analysis of the potential for harmful interference to radar altimeters from these new flexible use (5G) emissions. The results of the SC-239 analysis were published in a report (RTCA MSG Report) that demonstrated that there was indeed a credible risk of harmful interference to radar altimeters from new 5G emissions.

The results and implications of the RTCA MSG Report has generated considerable interest from both aviation and wireless industry stakeholders, as well as the government bodies that regulate each. This interest in the conclusions of the RTCA MSG Report has led to broad interest in reviewing the data that lead to the establishment of the interference tolerance masks that AVSI provided. This AVSI Report addresses this interest by providing both the raw data, and detailed descriptions of the derivation of these data, that establishes both the context in which the data must be interpreted and corresponding limitations on the application of these data to questions surrounding the potential for harmful interference to radar altimeters from new 5G sources. This AVSI Report also responds to some of the comments arising from public review of the RTCA MSG Report regarding test methods, selection of interference tolerance threshold criteria and other aspects of the AFE 76s2 project.

Based at Texas A&M University, AVSI is an aerospace industry research cooperative that facilitates collaborative research and technology projects for its members. This project included representatives from Airbus, Aviation Spectrum Resources Inc. (ASRI), Collins Aerospace, Embraer, Federal Aviation Administration (FAA), Garmin, Honeywell, the International Air Transport Association (IATA), Lufthansa Technik, National Aeronautics and Space Administration (NASA), Texas A&M University, Safran, and Thales. Project Participants contributed the subject matter expertise necessary to complete this project, including radar altimeter design engineers, aircraft systems integration experts, and aviation spectrum regulators.

This report is structured in three volumes:

- Volume I (this document) contains the introduction, test procedures, and test results from OOBI representative of 5G fundamental signals.
- Volume II contains the test results from in-band interference representative of 5G spurious signals. Also identifies changes to the test conditions and analysis for spurious tests.
- Volume III contains additional manufacturer-provided test results.

These will be released sequentially, upon completion and release approval of each individual Volume.

1 Introduction

1.1 Purpose of this Report

1.1.1 Report Objectives

This report publicly documents the procedures and results of Aerospace Vehicle Systems Institute (AVSI) radar altimeter[1] (RA) interference testing performed under AVSI Project AFE 76s2 – *Out-of-band Interference with Radio Altimeters* (AFE 76s2) aimed at determining the sensitivity of existing commercial radar altimeters to new 5G signals intended to operate in the 3700 – 3980 MHz frequency band.

The project was launched to obtain data that would be useful for establishing Standards and Recommended Practices (SARPs) for radar altimeters through the International Civil Aviation Organization (ICAO).[2] It was discovered in preliminary testing that RAs exhibited sensitivity to interference from orthogonal frequency-division multiplexed (OFDM) interference signals of various bandwidths and center frequencies in the 3700 – 4200 MHz frequency band.[3] This led to the detailed testing that determined interference tolerance thresholds that were subsequently provided to RTCA, Inc. for use in their analysis of the potential for harmful interference to RAs from new flexible use (5G) emissions in the 3700 – 3980 MHz band as proposed (and ultimately authorized) by the Federal Communications Commission (FCC) in their Report and Order released in March 2020.[4] The results of the analysis, conducted by a public multi-stakeholder group encouraged by the FCC and organized under Special Committee SC-239 (RTCA MSG), were published in a report that demonstrated that there was indeed a credible risk of harmful interference to RAs from new 5G emissions.[5]

The results and implications of the RTCA MSG Report has generated considerable interest from both aviation and wireless industry stakeholders, as well as the government bodies that regulate each. Intellectual property generated by AVSI Projects (Project Technology or PT) is generally protected from release to parties other than the Project Participants, but the interest in the conclusions of the RTCA MSG Report has led to broad interest in reviewing the data that lead to the establishment of the interference tolerance masks (ITMs) that were provided in the RTCA MSG Report. This AVSI Report addresses this interest by providing both the raw data, and detailed descriptions of the derivation of these data, that establishes both the context in which the data must be interpreted and corresponding

[1] Radar altimeters are also commonly referred to as "radio altimeters."

[2] *See* International Civil Aviation Organization (ICAO), Job Card FSMP.006.01, Nov. 24, 2016. Available at https://www.icao.int/safety/FSMP/Documents/Job%20Cards/FSMP_JobCard.06.01.pdf.

[3] *See* AVSI, *Behavior of Radio Altimeters Subject to Out-Of-Band Interference*, *attached* to Letter of Dr. David Redman, AVSI, to Marlene H. Dortch, Secretary, FCC, GN Docket No. 18-122 (filed Oct 22, 2019) (AVSI Preliminary Report); *see also* AVSI, *Effect of Out-of-Band Interference Signals on Radio Altimeters*, *attached* to Letter of Dr. David Redman, AVSI, to Marlene H. Dortch, Secretary, FCC, GN Docket No. 18- 122 (filed Feb. 4, 2020) (AVSI Supplemental Report).

[4] *See* Expanding Flexible Use of the 3.7 to 4.2 GHz Band, GN Docket No. 18-122, Report and Order and Order of Proposed Modification, 35 FCC Rcd 2343 (2020) (Report and Order).

[5] *See* RTCA, Inc., *Assessment of C-Band Mobile Telecommunications Interference Impact on Low Range Radar Altimeter Operations*, RTCA Paper No. 274-20/PMC-2073 (rel. Oct. 7, 2020), *attached to* Letter of Terry McVenes, President & CEO, RTCA, Inc., to Marlene H. Dortch, Secretary, FCC, GN Docket No. 18- 122 (filed Oct. 8, 2020) (RTCA MSG Report).

limitations on the application of these data to questions surrounding the potential for harmful interference to RAs from new 5G sources.

1.1.2 Release of AVSI Project Technology

AVSI imposes terms on all Projects that protect Project Technology from release by AVSI and other Project Participants unless all Project Participants unanimously agree to the release. In many cases, AVSI Project Participants have agreed to release data either in the public domain or under some form of written agreement as such release promotes the value of the project.

As AFE 76s2 specifically considered the performance of various RAs under radio frequency (RF) interference conditions, and the Project Participants included several RA manufacturers that produce competing products, it was agreed at the beginning of the project that interference test results would be considered Project Technology that would require unanimous approval to release outside of the project membership. Since the testing considers performance and testing to failure for very specific conditions, it was recognized that the data could be easily misinterpreted without understanding the proper context in which it was obtained.

AVSI Projects also occasionally consider the Background Proprietary Information (BPI) of one or more Project Participants when doing so will enhance the value of the project. Additional protections are placed on BPI and ownership of this type of intellectual property remains with the disclosing party. BPI has had very limited use on AVSI Projects, and in most cases was anonymized by AVSI by combining data from multiple sources to render it untraceable to any specific source. Specific terms governing the release of BPI are defined by the disclosing party and exclude AVSI from sharing the subject BPI with other parties without express authorization.

Given the number of requests for access to AFE 76s2 Project Technology, the Project Participants have concluded that it would be most efficient to release this report in order to allow additional independent review of the data and methods employed by AVSI.

1.1.3 Relationship to RTCA MSG Report

This report is based on AFE 76s2 Project Technology and is copyrighted by AVSI. As noted above, the data obtained under AFE 76s2 is AVSI PT that was aggregated, anonymized, and provided to RTCA to support their analysis under the RTCA MSG. The AFE 76s2 Project Management Committee (PMC) approved the release of the aggregated, anonymized data to RTCA. RTCA incorporated descriptions of this data and specifics of the AVSI AFE 76s2 test setup in the RTCA MSG Report, to which RTCA, Inc. owns the copyright. Questions concerning the content of the RTCA MSG Report should be directed to RTCA.

1.2 Anonymization & Aggregation

The raw data in this report were obtained during testing conducted by AVSI at Texas A&M University as part of this AFE 76s2 project. It includes performance data of various model RAs operating at different nominal heights above a simulated ground level while subject to RF interference applied to the receive (Rx) port of the RA under test. To maintain PT protection agreements, the PMC has agreed to release these data in a form that does not allow association of specific data to specific altimeter models. Thus, all references to the altimeters that were tested by AVSI in this project will use an arbitrary reference designator. These designators apply only to the data reported herein. There is no relationship to any similar designators reported in any other forum or publication, specifically, there is no relationship to the designators used in the RTCA MSG Report other than association into the Usage Categories (UCs) established by AVSI prior to providing aggregated data to RTCA.

Note that anonymized data is sufficient to confirm the analysis in the RTCA MSG Report since the RTCA MSG received only anonymized, aggregated data. However, access to raw anonymized data will further allow researchers to validate the derivation of the aggregate ITMs reported in the RTCA MSG Report.

Note that AFE 76s2 results were provided to RTCA aggregated by UC, as it was understood that all RAs must be assessed against potential harmful interference, thus all RA models in a given UC were included in the aggregation for that UC. AVSI did not exclude the best and worst performers for example. This is effectively the same as computing the ITMs for each RA tested, and then drawing a worst case envelope for all altimeters in a UC over the plotted ITMs.

While performance of different RA models under OOBI conditions varied, this report presents the data measured by AVSI for all RAs tested, without inference as to the relative quality of the designs of the individual models. All models tested by AVSI were current production units that were verified by their manufacturers to be in conformance with minimum performance standards (MPS) according to Federal Aviation Administration (FAA) requirements. The RA models tested have been reliably used for many years in a variety of aircraft and applications.

1.3 Limits on Use of AVSI Data

It is important to emphasize that the data reported herein were collected using a set of assumptions and for a very specific purpose, namely to establish ***if*** there is a risk of harmful interference to RAs from new flexible use services operating in the 3700 – 3980 MHz frequency band.

To answer this question, production commercial RAs were tested in a benchtop test rig consisting of an operational height simulator and programmable interference sources. Specific scenarios, including the Worst Case Landing Scenario (WCLS), developed under AVSI Project AFE 76s – *Wireless Avionics Intracommunications (WAIC) Requirements* and vetted by ICAO and RTCA, were simulated using best available knowledge of the test parameters.[6] The RAs were subjected to increasing levels of RF interference power applied to the standard input of the RA under test, and the effects were observed on the standard output of the RA under test, which was an ARINC 429 digital output in most cases. This testing does not make use of proprietary design information concerning the specific receiver features and performance for each RA that was tested. Such information was not provided to AVSI. As a result, this “black box” testing does not allow determination of specific failure mechanisms causing the reported height errors or NCDs that were observed on the standard output. It is sufficient, however, to establish causation of RA errors, including hazardously misleading information (HMI) and no computed data (NCD) errors, from RF interference conditions that can impact aircraft operations and safety.

Furthermore, this testing was not intended to validate compliance of the RAs with the performance requirements in the applicable FAA Technical Standard Order (TSO) MPS.[7] The test rig was configured

6 *See* ICAO FSMP, Information Paper FSMP-WG/7 IP/15, Radio Altimeter Interference Susceptibility Testing Status Update, 6 – 13 Sep 2018. Available at https://www.icao.int/safety/FSMP/MeetingDocs/FSMP WG7/IP/FSMP-WG07-IP15_WAIC Update.docx.

7 *See* FAA, TSO-C87a, *Airborne Low-Range Radio Altimeter* (May 31, 2012) (TSO-C87a) at 1 (stating that the applicable minimum performance standard is “EUROCAE document ED-30”). *See also* EUROCAE, ED-30, *Minimum Performance Specification for Airborne Low Range Radio (Radar) Altimeter Equipment* (March 1980) (ED-30). TSO-C87a also references RTCA DO-155, but only for the calculation of external loop loss. *See* TSO-C87a at 8. *See also* RTCA, Inc., DO-155, *Minimum Performance Standards Airborne Low-Range Radar Altimeters* (Nov. 1, 1974) (DO-155). Prior to the introduction of TSO-C87a, the minimum performance standards had been defined directly within the TSO document, TSO-C87, without reference to any external

to test for a differential measurement between the height reported in the presence of RF interference and the height report with no RF interference in order to isolate the effect of the 5G RF interference (i.e., how the 5G signal changed the RAs response under normal operation). All of the RAs tested were manufactured between January 2012 and February 2020 and are models still in production under the applicable TSOs issued to manufacturers. The RA manufacturers supplying test units verified that each unit operated in accordance with the necessary standards and certification in the absence of RF interference.

Finally, the criteria used to define “harmful interference” was adopted from the previous in-band interference susceptibility testing performed under AVSI Project AFE 76s1 – *WAIC Requirements – Supplement 1*. Namely, the criteria attempted to quantify the observable effects solely attributable to 5G external RF interference using measurements of relative changes to the RA output. This is different than TSO MPS compliance testing, which seeks to validate that a RA meets its performance requirements throughout a specified range of operating environments, and which thus evaluates *absolute accuracy* against specified limits.

The rationale for using the AFE 76s1 definition of “harmful interference” stems from the insistence of the aviation community (through ICAO) to strictly adhere to Rec. ITU-R M.2059 recommended protections for RAs, namely that WAIC signals operating in the 4200-4400 MHz frequency band observe an I_{WAIC}/N_{RA} limit of -6 dB (which represents a rise of 1 dB in the noise floor of the RA receiver).[8] As was the case for the OOBI testing described herein, the specific receiver noise characteristics were not available in the WAIC-RA interference black box testing. Thus, it was assumed that the onset of observable effects on the standard output would provide the closest indication that WAIC power levels had reached the I_{WAIC}/N_{RA} limit. WAIC signals that were strong enough to drive the RA output outside the TSO MPS accuracy specifications were assumed to be significantly higher than this limit. Thus, the aviation industry held itself to the highest levels of safety analysis by insisting that worst-case assumptions leading to the maximum potential levels of WAIC interference be compared to strict ITU-R coexistence criteria.

The OOBI testing described herein similarly followed accepted aviation safety analysis by simulating the worst case conditions allowed by regulation and observing the standard output to determine the onset of observable effects attributable to OOBI.

1.4 Additional Data

1.4.1 Independent Corroboration of AVSI Test Results

The testing performed within the scope of AFE 76s2 was completed with the delivery of aggregated data to RTCA. Since that time, AVSI understands that several RA manufacturers have been performing their own internal testing of the range of altimeter models they produce. While yet to be released, initial data validates the AVSI testing methodology and results. Some of this data has been released to AVSI under agreement and will be incorporated in subsequent volumes of this report to present this validation in the public record.

documents, such as DO-155. *See* FAA, TSO-C87, *Airborne Low-Range Radio Altimeter* (Feb. 1, 1966) (TSO-C87).

[8] Recommendation ITU-R M.2059, *Operational and Technical Characteristics and Protection Criteria of Radio Altimeters Utilizing the Band 4 200-4 400 MHz* (02/2014) (Rec. ITU-R M.2059) at 19-20.

1.4.2 Additional Radar Altimeters

In addition to retesting some altimeter models tested by AVSI in this project, the RA manufacturers had access to other RA models they produce but were not available to AVSI at the time of AFE 76s2 testing.

As was described in the AVSI Preliminary Report and AVSI Supplemental Report, RAs can be grouped into different UCs based on typical installations and applications. The different UCs include RAs with roughly similar performance characteristics. Thus, the data from these additional RA models that is provided to AVSI will be presented in the context of the relevant UC in order to provide a basis for comparing the results from these models with those tested by AVSI in this project.

1.4.3 Other Testing

There has been additional testing performed by different interests throughout the world. Namely, Japan has performed similar interference testing, which was reported to the ICAO Frequency Spectrum Management Panel (FSMP).[9] Additional testing is being planned by the U.S. Department of Defense (DoD) under the Joint Interagency 5G Radar Altimeter Interference (JI-FRAI) initiative. This effort, which is just beginning, includes bench testing. Inputs have been provided by AFE 76s2 and subsequent RA manufacturer test methods and considers the range of RAs used in the U.S. DoD fleet (both military-specific RA models and civil models used in DoD aircraft – the majority of which are different than the models tested by AVSI).

1.5 Report Structure

This report is structured in three volumes:

- Volume I (this document) contains the introduction, test procedures, and test results from OOBI representative of 5G fundamental signals.
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1.6 About AVSI

Based at Texas A&M University, AVSI is an aerospace industry research cooperative that facilitates collaborative research and technology projects for its members. This project included representatives from Airbus, Aviation Spectrum Resources Inc. (ASRI), Collins Aerospace, Embraer, Federal Aviation Administration (FAA), Garmin, Honeywell, the International Air Transport Association (IATA), Lufthansa Technik, National Aeronautics and Space Administration (NASA), Texas A&M University, Safran, and Thales. Project Participants contributed the subject matter expertise necessary to complete this project, including radar altimeter design engineers, aircraft systems integration experts, and aviation spectrum regulators.

9 *See* ICAO FSMP, Information Paper FSMP-WG/7 IP/08, Experimental investigation of adjacent-band interference into radio altimeter due to LTE-Advanced base stations, 6 – 13 Sep 2018. Available at https://www.icao.int/safety/FSMP/MeetingDocs/FSMP WG7/IP/FSMP-WG07-IP08_RA_LTE-Advanced_Adjacent_Band_Interference_Experiments_rev1.doc.

2 Test Procedures

2.1 Test Setup

The AVSI test setup used to investigate the effect of RF interference on RA performance was adapted from recommendations in RTCA DO-155 and EUROCAE ED-30, which consisted of bench mounted commercial off-the-shelf RAs operating with an operational height simulator and accompanying instruments to measure performance. The AVSI test setup then input various sources of RF interference directly into the RA return signal path, all while monitoring the measured height reported on the standard RA output.

Figure 2-1 presents a block diagram of the AVSI test setup. All tests described in this report were conducted in a laboratory setting under standard environmental conditions. The main features of the apparatus include connections for the altimeter under test (green block), an operational height simulator (pink block), simulation of frequency modulated continuous wave (FMCW) interference sources operating in the 4200 – 4400 MHz band (blue block), simulation of 5G interference sources (blue block), data acquisition, and computer control. Each of these are described in detail below.

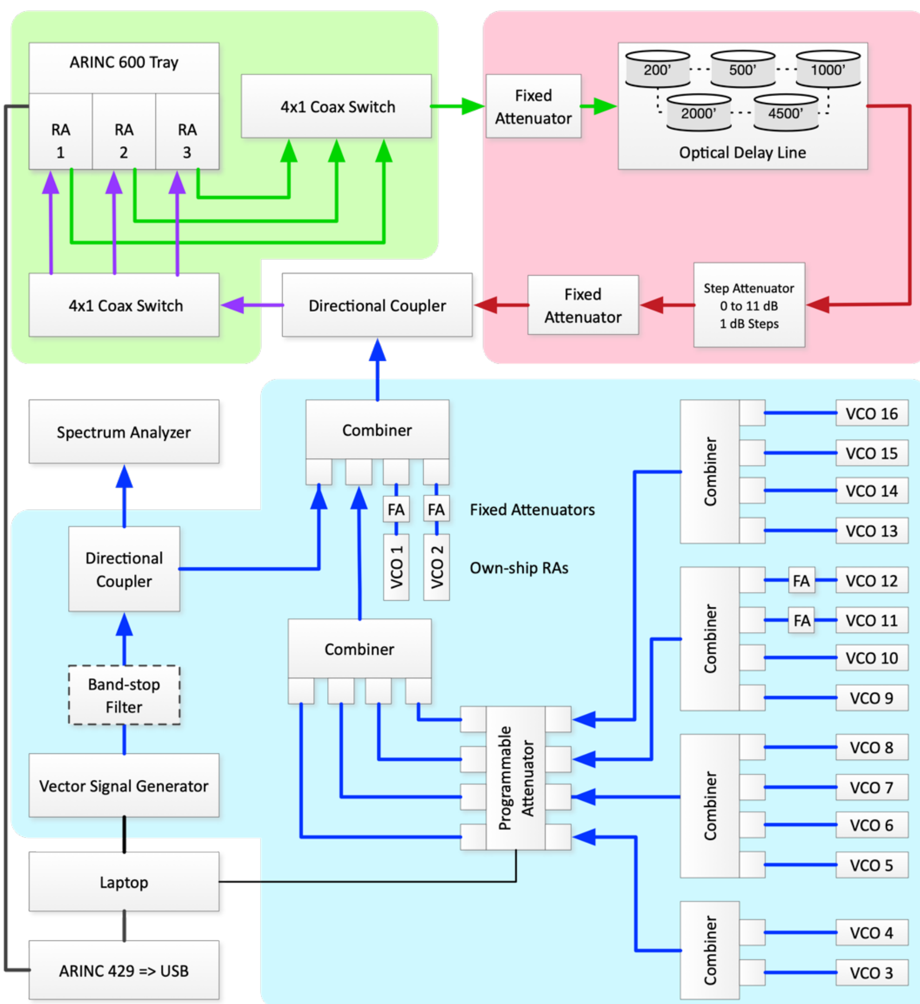


Figure 2-1: AVSI Test Schematic

2.1.1 Altimeters Under Test

AVSI obtained a total of nine different commercial RA models from five separate international manufacturers. Each of the nine altimeters has at least 1700 units in operation in various aircraft and the total number of deployments in the U.S. for all nine altimeter models is more than 66,000 units. While all units were produced under applicable TSOs and thus meet performance requirements necessary for installation in a certified aircraft, they differed in the types of aircraft in which they were intended to be installed and operated. The altimeter models used in the AVSI tests and characteristics relevant to the testing are listed in Table 2-1.

Table 2-1: Radar Altimeter Models Used in Interference Tolerance Testing

RA Model	Modulation	Maximum Height†	Maximum Installation††
A	FMCW	2500 ft	Triple
F	FMCW	5500 ft	Triple
I	FMCW	2500 ft	Single
L	FMCW	5500 ft	Triple
S	FMCW	2500 ft	Triple
T	FMCW	7500 ft	Triple
V	Pulsed	2500 ft	Dual
X	FMCW	5500 ft	Triple
Y	FMCW	5500 ft	Triple

† – The maximum height corresponds to the maximum at which each radar altimeter model is designed to provide a reliable height measurement and meet all performance requirements. However, radar altimeters generally remain operational at all heights throughout all phases of flight.

†† – The maximum installation refers to multiplex installations onboard a single aircraft. The configurations listed for each altimeter are the maximum allowed, though aircraft installations may use fewer than the maximum (e.g., Altimeter A can be found in single, dual, or triplex, installations depending on the airframe).

To allow for more relevant comparison of RA performance when subjected to RF interference, AVSI defined three Usage Categories that group together RAs with similar intended installations and applications. The Usage Categories were defined as shown in Table 2-2.

Table 2-2: Usage Category Definitions

Usage Category	Description	RAs Included in UC
UC1	RAs installed in larger single-aisle and wide-body commercial air transport airplanes	F, L, T, X, Y
UC2	RAs installed in all other fixed-wing aircraft not included in Usage Category 1, including regional air transport, business aviation, and general aviation airplanes	A, I, S, V
UC3	RAs installed in transport and general aviation helicopters	A, I, S, V

RAs in UC1 generally have more stringent performance requirements than RAs in UCs 2 and 3, since these RAs are used in a wider variety of safety-critical systems that enable safe operation of commercial airliners in all-weather conditions. Also, for this reason, all RAs in UC1 are capable of being installed with up to three units per aircraft. Installation manuals produced by the RA manufacturers provide aircraft integrators with requirements for installation in order to ensure that triplex RA installations minimize mutual interference between units. The AVSI test apparatus included the effects of multiple installations by simulating the waveform of the RA under test using voltage-controlled oscillators (VCOs) as described in Section 2.1.3.1. Additionally, RAs in UC1 operate to heights above ground level (AGL) of 5500 feet (ft) or higher. Altimeter T reports measured heights up to 7500 ft AGL.

RAs in UCs 2 and 3 are the same RA models (that is, all models applicable to UC 2 are also applicable to UC 3), separated into two distinct UCs based on differences in application or operating environment. Similar simulation of on-board altimeters was used for those RAs that accommodate multiplex installations. The only RA tested that was specified only for single installations was Altimeter I, in which case both VCOs simulating on-board multiplex RAs were turned off. Further, Altimeter V, which is a pulsed altimeter, is not expected to have significant performance impacts associated with mutual interference in a dual installation.[10] Because of this, and the complication associated with generating a suitable pulsed waveform to adequately represent a multiplex installation, no on-board interference was simulated for Altimeter V. Additionally, UC2 / UC3 units are specified for operation up to only 2500 ft AGL.

With the exception for Altimeter V, all RAs that were tested by AVSI output measured height over a digital avionics bus (ARINC-429).[11] Altimeter V uses a precision analog output voltage proportional to the measured height, which was sampled and recorded.

For testing, RAs were mounted per recommended installation procedures provided by each RA manufacturer under their proprietary installation guidelines for airframers. UC1 RAs were mounted in a standard ARINC 600 avionics tray with the recommended avionics connector. This connector is used to pin configure the RA for a specific installation assignment, which is used for configuring RAs in multiple-unit installations. The RAs have a System Select input (typically pin configured, but some have a voltage input) to internally configure operating parameters that allow multiple RAs of the same model on the same aircraft to operate simultaneously with high reliability. Since AVSI could not simultaneously test multiple RAs of each model, each RA was set to System Select 2. A test rack was constructed to allow three different RAs to be mounted with the radar altimeter under test (AUT) selected with a panel switch as shown in Figure 2-2. This switch operated a Teledyne CCR-38S SP4T coaxial (coax) switch whose inputs were connected to the RA transmit outputs (Tx) and whose output was connected to the operational height simulator using manufacturer recommended, aircraft-grade coaxial cabling. A second equivalent RF coaxial switch was used in the RA signal return path, connecting the operational height simulator output to the receive inputs (Rx) of the RA mounted in the test rack. The test rack also provided 115 VAC 400 Hz power or 28 VDC power to the AUT as required.

[10] This particular RA design uses a fixed narrow pulse width resulting in a low duty cycle (approximately 0.1%), and pulse repetition interval (PRI) jitter to prevent performance impacts of mutual interference in a dual installation. However, not all pulsed altimeter designs will have such negligible mutual interference impacts, particularly those designed to operate up to higher maximum altitudes.

[11] Aeronautical Radio, Inc., ARINC Specification 429P1-19*, Digital Information Transfer System (DITS), Part 1: Functional Description, Electrical Interfaces, Label Assignments and Word Formats* (last published January 2019).

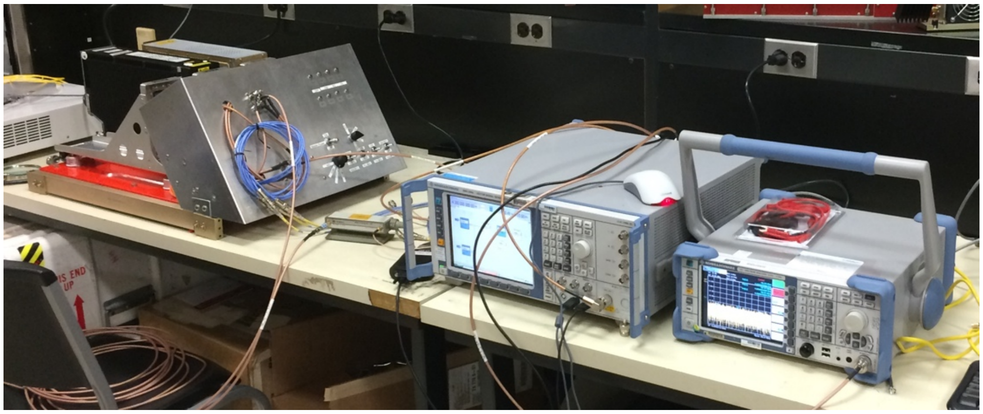


Figure 2-2: AVSI Test Bench

The ARINC 429 digital output was connected to the control computer via a Ballard Technology USB 429 interface adapter connected to the test laptop computer. All RAs in UC1 reported measured height on an ARINC 429 output, as did all but one of the UC2/UC3 RAs. Reporting rates were typically 30 readings per second with a height resolution of 1 foot or less.

UC2 and UC3 RAs were mounted directly on the benchtop and connected to the ARINC 429 interface using a pigtailed connector that provided connections to power and the standard output, except for Altimeter V, for which the precision analog output and two additional discrete signals that indicate tracking validity and error conditions (equivalent to validity and error flag messages reported on the ARINC 429 bus for all other altimeters) were monitored using a National Instruments USB-6211 analog-to-digital converter connected to the test laptop computer.

2.1.2 Operational Height Simulator

AVSI testing used an operational height simulator that consisted of a fiber optic delay line with additional fixed and step variable attenuators to set the appropriate signal delay and attenuation of the RA RF output. This was adapted from the test configuration recommended in DO-155, which specifies that the "altitude simulator consists of variable and fixed RF attenuators, and coaxial cables or other suitable delays to simulate the various altitudes. The simulator must accept the altimeter energy, attenuate and delay this RF energy and present the delayed signal of the altimeter receiver."[12]

The AVSI test setup used an Emcore 5021TR-B-1309-FA fiber optic transceiver and optical fiber spools providing calibrated delays representing round trip propagation for operational heights of 200, 500, 1000, 2000, and 4500 feet. The individual spools can be daisy-chained to provide additional test operational heights. A 20 dB fixed attenuator was inserted prior to the optical transceiver to protect the transceiver from input levels that could cause damage. The external loop loss for the full RA Tx to Rx signal path was set by inserting additional attenuators and then measuring the total attenuation using a calibrated network analyzer over the 4200 – 4400 MHz frequency band. A 0 to 11 dB step attenuator was used to bring the total loop loss to the external loop loss value specified by DO-155 for the operational height being simulated.[13] These loop loss values, which are the basis for performance requirements specified by the FAA, are defined for *external* loop loss and do not include cable losses

[12] DO-155 Appendix A at 2.

[13] While the methods for calculating external loop loss specified in DO-155 were used, the assumed terrain backscatter coefficient was 0.01 instead of 0.006. This corresponds to the minimum value specified in ED-30 for testing of RA performance requirements, and results in a 2 dB relaxation of the full DO-155 loop losses.

between the RA unit and the Tx and Rx antennas. Therefore, cable losses must be incorporated in the total loop loss values used for testing to account for all losses in the as-installed systems in order to accurately simulate the signal and interference powers that would reach the RA Rx input port in actual conditions. Since every RA tested in this study requires the use of such cabling to operate, an additional 6 dB to account for cable losses between the RA Tx and Rx ports and the RA Tx and Rx antennas was added to the DO-155/ED-30 values. While individual RA manufacturers specify an acceptable range for antenna cable in their installation manuals, the radar altimeter and aircraft integration experts on this project agreed that 6 dB total cable loss (3 dB in both the Tx and Rx paths) was appropriate for the testing and complied with the manufacturers' installation guidance for all RA models being tested.

2.1.3 Interference Sources

Figure 2-3 illustrates the sources of RF interference that can be received by an RA while in operation that were considered in the AVSI testing (although not all sources were considered concurrently). These consist of RF emitters on board the same aircraft carrying the RA experiencing interference ("victim RA"), such as multiple RAs in a dual or triplex installation or 5G user equipment carried on board the aircraft; and RF emitters off board the aircraft, such as RA signals from other aircraft and 5G base stations on the ground. These sources of interference can be classified by the part of the spectrum occupied by their fundamental emissions, either being within the 4200 – 4400 MHz frequency band ("RA-band") or outside the RA-band, but close enough in frequency to be detected by the victim RA. As shown in Figure 2-3, in-band sources included other RAs that are within radio range of the victim RA's receive antenna and spurious signals from C-band 5G emitters. Out-of-band emitters considered in this testing were limited to fundamental signals from new 5G emitters proposed for operation in the C-band from 3700 – 3980 MHz.

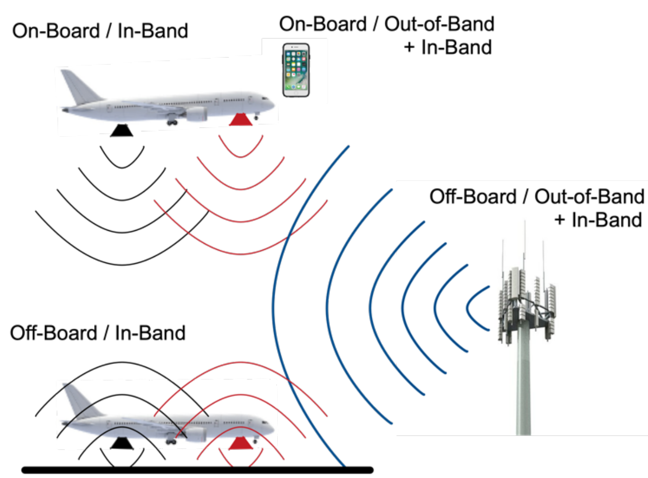


Figure 2-3: Sources of RF Interference

2.1.3.1 Simulation of Other RA In-Band Interference Sources

Most, if not all, RAs in UC1 experience interference from other RAs operating in the same 4200 – 4400 MHz frequency band in almost all phases of flight. This interference originates from two to three RAs being installed on the same aircraft, as well as from RAs operating on nearby aircraft during certain operations. RAs in categories UC2 and UC3 will similarly experience such interference. Though some aircraft in these categories do not use dual or triplex installations, such interference is still experienced when operating near other aircraft. Existing RAs are designed to operate reliably over the full range of specified environmental conditions in an ambient RF environment that was defined prior to the introduction of new C-band 5G signals. Thus, to test the potential effects of these new 5G signals in actual conditions, AVSI simulated in-band FMCW interference from other RAs to establish a representative noise floor in the RA under test prior to the introduction of out-of-band 5G fundamental signals and representative 5G spurious in-band signals.

Additional RA FMCW interference signals were generated using Mini-circuits ZX95-4403-S+ VCOs. Each VCO was controlled by an independent function generator that supplied the proper waveform to the voltage tuning input in order to assure that individual FMCW sources were uncorrelated. Most of the FMCW RAs that were tested use a continuous triangle-wave linear up/down chirp; however, some use a sawtooth frequency modulation waveform. VCOs were calibrated to simulate the sweep characteristics of specific RAs by determining the DC voltage that established a center frequency of 4300 MHz and the minimum/maximum voltages necessary to cover the specific RA sweep range (ranging from approximately 100 to 160 MHz, depending on the RA model).

<u>Simulation of On-Board / In-Band FMCW Interference Sources</u>

For RAs that are configurable for multiplex installations, the DC offset, waveform peak voltages, sweep repetition frequency, and sweep waveform of the function generators driving one or two VCOs were configured to replicate the frequency sweep characteristics of the AUT, adjusted for any changes caused by setting the System Select input to 1 or 3. This was necessary to simulate in-band interference originating from the other RAs operating simultaneously on board the same aircraft.

For each of the RA models that were tested with on-board multiplex installation interference (that is, all models except Altimeter I and Altimeter V), the RA manufacturers were consulted to define the appropriate antenna isolation assumptions for a multiplex installation in accordance with their standard installation guidance. The resulting power level for each own-ship VCO's RF output was set such that the power measured at the AUT Rx input matches the nominal AUT Tx output power attenuated by the manufacturer's specified minimum antenna isolation (ranging from 60 to 70 dB) plus 6 dB for cable losses. This attenuation between the VCO RF output and the AUT Rx input was then verified using a network analyzer over the 4200 – 4400 MHz frequency band.

Simulation of Off-board / In-Band FMCW Interference Sources

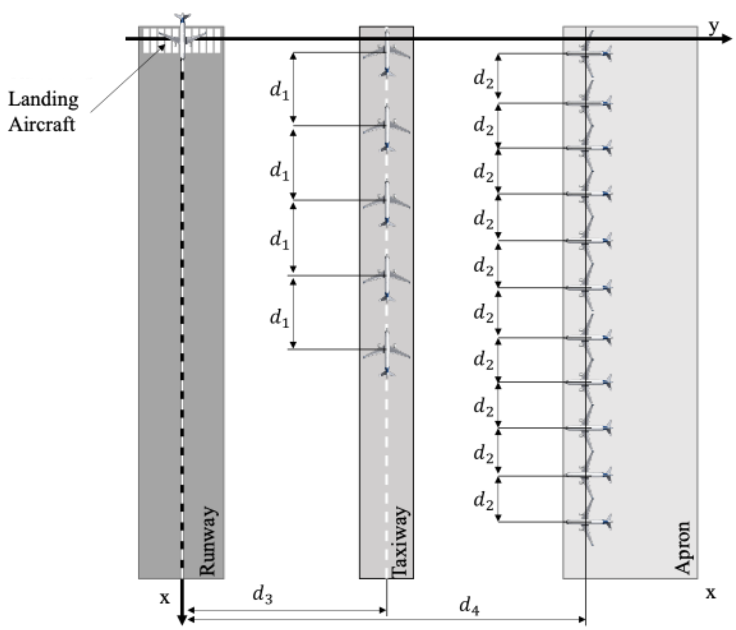
Supported by RA manufacturers and aviation standards bodies, AVSI had previously conducted an extensive analysis of potential operating scenarios to determine the worst-case risk in terms of severity and likelihood of occurrence of the loss of RA function or erroneous RA operation due to RF interference. This led to the creation of a worst-case landing scenario (WCLS), which has been vetted by the aviation community, in which a victim RA is located on an aircraft landing at a busy airport. Since RAs are always turned on from gate-to-gate, this scenario incorporates in-band interference from other aircraft on the ground in proximity to the landing aircraft. The greatest number of RAs that could simultaneously impact the victim RA was computed by considering the most-dense configuration allowed by US and international aerodrome operation regulations of aircraft on the ground, and the slant range from these aircraft to the victim RA Rx antenna along the glide slope of the landing aircraft. A height of 200 ft AGL was considered since previous similar analysis considering omnidirectional radiation of WAIC signals from WAIC-equipped aircraft in the same configuration determined that 200 ft was the worst-case height. Although Figure 2-4 shows this height corresponding to the point at which the landing aircraft crosses the runway threshold, this does not need to be the case. Instead, this is the height of the landing aircraft at the point at which it is in-line with the first of the lined-up aircraft on the taxiway and/or apron. Such a geometry can occur well before the runway threshold crossing in cases where the taxiway and/or apron extend beyond the end of the runway, which is common at many airports.

The WCLS identifies a set of sixteen aggressor aircraft, of which five aircraft are in the taxiing phase in proximity to the landing victim aircraft, and eleven aircraft are farther away on the aerodrome's apron, as illustrated in Figure 2-4. Coupled with the assumed height of 200 ft AGL, this geometry allowed for the calculation of anticipated levels of interference at the input to the victim RA from all sixteen aircraft, based on free space path losses, specular reflection off the tarmac, and representative antenna gains. The geometry of the WCLS includes the separation distances d_1, d_2, d_3 and d_4 relevant for parameterization of the WCLS and specified in Annexes 10 and 14 of the Convention on International Civil Aviation as well as the IATA Airport Development Reference Manual.[14] These are summarized in Table 2-3.

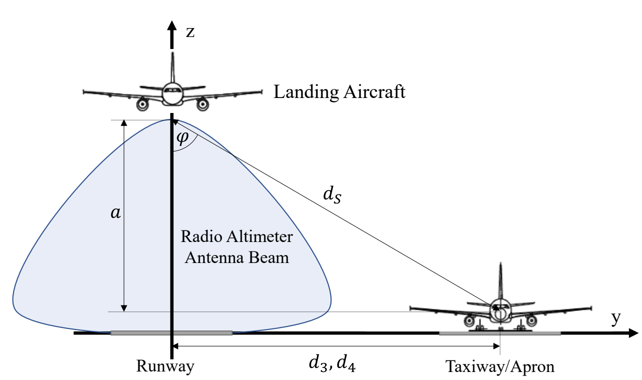
[14] ICAO Annex 10, "Aeronautical Telecommunications – Volume I – Radio Navigational Aids" – 7th edition (July 2018). Available from ICAO Store at: https://store.icao.int/en/annex-10-aeronautical-telecommunications-volume-i-radio-navigational-aids. ICAO Annex 14, "Aerodromes – Volume I – Aerodromes Design and Operations" – 8th edition (July 2018). Available from ICAO Store at: https://store.icao.int/en/annex-14-aerodromes. IATA, "Airport Development Reference Manual (ADRM)" – 11th edition (March 1, 2019). Available from IATA Store at: https://www.iata.org/en/publications/store/airport-development-reference-manual/.

Table 2-3: WCLS Geometry Explanation

Distance	Description
d_1	**Separation between two taxiing aircraft** The separation distance d_1 depends on aircraft type. For the assessments carried out in this test campaign, large aircraft with triplex RA installations were assumed. For these types of aircraft, a separation distance of $d_1 = 80$ m is considered reasonable based on existing airport designs and operations.
d_2	**Lateral separation between two parking aircraft** The separation $d_2 = 80$ m is the width of a standard parking box for many airports.
d_3	**Separation between centerline of runway and parallel taxiway** The minimum separation distance, d_3 , between the centerline of a runway and a taxiway on airport types 2B and 3B is specified as 87 m (see Annex 14 to the Convention on International Civil Aviation, section 3.9.8 Table 3-1).
d_4	**Separation between runway centerline and closest aircraft on the apron** For protection of ILS operation for precision approach CAT II/III, the localizer critical and sensitive area is defined in Annex 10 to the Convention on International Civil Aviation, Attachment C. The minimum separation between runway centerline and the RA transmit antenna location of an aircraft on the apron parking area is $d_4 = 300$ m, as derived from Figure C-4A of Annex 10 to the Convention on International Civil Aviation, Attachment C.



(a)



(b)

Figure 2-4: Worst Case Landing Scenario (WCLS)
(a) Distribution of aggressor aircraft on taxiway and apron,
(b) Vertical and lateral separation of victim and aggressor aircraft.

The AVSI experimental apparatus was limited to 16 VCOs, 2 for own-ship signals and 14 for off-board signals. VCOs 3 to 16 were configured subject to the constraints of the experimental apparatus to present sufficiently representative WCLS interference at the AUT Rx input. Chirp rates and bandwidths were set to simulate a variety of different commercial RA models, and the power levels were configured to account for interference path loss values, Tx power for the aggressor RAs, and cable losses on both the aggressor and victim aircraft, subject to experimental limitations. Each VCO has a nominal output power of 4 dBm, and combinations of fixed and programmable attenuators were used to set the interference power at the AUT Rx input according to the values in Table 2-4. Note that the own-ship VCO settings are configured according the parameters of the specific AUT (and for Altimeter I and Altimeter V, they are disabled altogether).

As the values in Table 2-4 demonstrate, in-band FMCW interference is dominated by own-ship sources for RAs tested in multiplex installations, and the WCLS off-board sources have no significant impact. For RAs tested in a single installation configuration, only the off-board sources at -62 dBm contribute significantly to the total in-band interference. This demonstrates that while the WCLS was created to provide fidelity in achievable worst-case operational scenarios, the off-board FMCW interference is dominated by one or two aircraft on the taxiway near the runway. Therefore, the test results apply to a wider range of scenarios than just the full WCLS geometry.

Table 2-4: WCLS VCO Settings

VCO	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	units
Output Power	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	dBm
Fixed Attenuation	-18	-18	0	0	0	0	0	0	0	0	-23	-23	0	0	0	0	dB
Programmable Atten.	n/a	n/a	-56	-56	-26	-26	-26	-26	-26	-26	-26	-26	-49	-49	-49	-49	dB
Other Circuit Losses	-16	-16	-40	-40	-40	-40	-40	-40	-40	-40	-40	-40	-40	-40	-40	-40	dB
Power at RA Rx	**Per AUT**	**Per AUT**	**-92**	**-92**	**-62**	**-62**	**-62**	**-62**	**-62**	**-62**	**-85**	**-85**	**-85**	**-85**	**-85**	**-85**	dBm
Sweep Repetition Rate	**Per AUT**	**Per AUT**	143	111	133	133	133	118	118	118	111	129	129	129	143	143	Hz
Sweep BW	**Per AUT**	**Per AUT**	133	131	131	124	132	135	132	132	124	130	129	131	131	132	MHz
Sweep Waveform	**Per AUT**	**Per AUT**	/\/\/	/\/\/	/\/\/	/\/\/	/\/\/	/\/\/	/\/\/	/\/\/	/\/\/	/|/|/|	/|/|/|	/|/|/|	/\/\/	/\/\/	

2.1.3.2 *Simulation of 5G Fundamental Interference Sources*

AVSI studied both simulated 5G fundamental emissions in the 3700 – 3980 MHz frequency band and spurious emissions in the 4200 – 4400 MHz frequency band. A Rohde & Schwarz (R&S) SMW200A vector signal generator (VSG) was used to simulate 5G emissions with high fidelity. The SM200A VSG was outfitted with the SMW-K144 5G NR and SMW-K62 software options, allowing for the generation of 3GPP-compliant 5G NR test waveforms at frequencies ranging from 3700 – 3980 MHz to simulate 5G fundamental emissions and additive white Gaussian noise (AWGN) signals between 4200 – 4400 MHz to simulate 5G spurious emissions.

<u>Simulation of 5G Fundamental Emission Sources</u>

The R&S SMW-K144 5G NR software provides a full library of 3GPP-compliant test models. The 5G NR Frequency Range 1 (FR1) test model 1.1 (NR-FR1-TM1.1) waveform was used for 5G fundamental emission testing. NR-FR1-TM1.1 is an Orthogonal Frequency-Division Multiplexing (OFDM) waveform using Quadrature Phase-Shift Keying (QPSK) subcarrier modulation and 30 kHz subcarrier spacing (SCS). The bandwidth was set to 100 MHz and tolerance thresholds for three center frequencies (3750, 3850, and 3930 MHz) were determined to provide full coverage of the frequency band defined in the FCC Report and Order. Thus, this testing used a number of subcarriers determined by the interference signal bandwidth and fixed SCS. By contrast, previous AVSI testing used OFDM signals of various bandwidths with variable SCS and a fixed number of subcarriers (52) modulated with Binary Phase-Shift Keying (BPSK) random data. While both waveforms were OFDM, in the testing described here, the NR-FR1-TM1.1 waveform provided more fidelity in the simulation of possible 5G fundamental emissions.

Because the response of RA receivers to RF signals inside the 4200 – 4400 MHz band is significantly different from the response to signals outside the band, the experimental apparatus was configured with a band-stop filter between the 5G signal source and the RA receivers for the fundamental testing, to avoid corrupting the test results due to incidental spurious emissions from the VSG that could land within the 4200 – 4400 MHz band. Because the filter response is non-zero in the 3700 – 3980 MHz frequency region (see Figure 2-9), the frequency-dependent insertion loss of the filter must be taken into account when deriving the interference power threshold referenced at the AUT Rx input from the VSG's commanded power output. For each of the 3750, 3850, and 3930 MHz center frequencies, the required compensation was determined by measuring the 100 MHz channel power (using the 5G OFDM waveform) at the AUT Rx input, both with and without the band-stop filter installed. To compute the 5G emission power at the AUT Rx input, these compensation values are applied to the nominal attenuation measured without the filter installed. The compensation values are summarized in Table 2-5.

Table 2-5: Band-stop Filter Correction Values for Computing 5G Fundamental Emission Powers at the AUT Rx Input Port

Center Frequency	Filter Correction Value
3750 MHz	1.2 dB
3850 MHz	1.9 dB
3930 MHz	4.5 dB

Simulation of 5G Spurious Emission Sources

An AWGN signal with sufficient bandwidth to cover the full receive bandwidth of the AUT (or intermediate frequency bandwidth in the case of pulsed altimeters) was selected as a suitable waveform for simulating 5G spurious emissions. The maximum bandwidth of the SMW200A VSG configured with the SMW-K62 software option for testing of the interference tolerance thresholds in the 4200 – 4400 MHz band was limited to 160 MHz, which was sufficient to cover the maximum receive bandwidth of all RAs tested. For 5G spurious emission threshold measurements, the band-stop filter was removed and the VSG was configured to produce a 160 MHz AWGN signal centered at 4300 MHz.

2.1.4 Data Acquisition and Experiment Control

The AVSI test apparatus used computer-controlled automation to implement the tests described in Section 2.2 and collect data from the AUT. The VSG was connected to a laptop computer (PC) through Ethernet. Custom Python software was used to manage the RF output state by sending standard commands for programmable instruments (SCPI) from the PC to the VSG, including output power, waveform, bandwidth, and center frequency. Commands issued to the VSG that changed the VSG's

RF output state were time stamped and logged with the RF output state value (ON/OFF). The AUT was not controlled by computer and had to be manually powered up and allowed to warm up before running any tests.

RAs with an ARINC 429 digital output (all units tested except Altimeter V, which used a precision analog voltage output sampled at about 25 Hz) were connected to a Ballard USB 429 adapter connected to the PC's USB input to convert ARINC 429 data to universal serial bus (USB). The interface was controlled and ARINC 429 data was acquired based on the update rate of each model (which ranged from 6 to 36 readings per second) using Ballard Co-Pilot software. The Python code ran asynchronously with the Co-Pilot software, and timestamped ARINC 429 height data was saved in a separate file. Post-processing of the time stamped VSG output state data and the time-stamped height data correlated the VSG stimuli with the AUT response.

2.1.5 Test Rig Characterization

2.1.5.1 Calibration and Characterization Tests

The test rig was fully calibrated to ensure accurate determination of the interference power thresholds. This included characterizing the spectrum analyzer, vector signal generator, and test rig attenuations in all signal paths.

<u>Spectrum Analyzer</u>

A Rohde & Schwarz FSV7 spectrum analyzer was used to characterize the 5G signals used in testing. The published specifications for the FSV7 indicate that the measurement noise floor (displayed average noise level) between 3600 MHz ≤ f < 6000 MHz is less than -148 dBm in a 1 Hz bandwidth.[15] The specified noise power of -148 dBm/Hz correlates to -65 dBm total power over 200 MHz.

The AVSI FSV7 instrument was characterized by terminating the input with a matched 50 Ω termination and measuring the power in the 200 MHz channel bandwidth between 4200 – 4400 MHz. With the resolution bandwidth (RBW) set to 300 kHz, the total power in the band is -67 dBm/200 MHz or -150 dBm/Hz, which complies with the published FSV7 specifications.

<u>Vector Signal Generator</u>

5G fundamental and spurious emissions were generated with a Rohde & Schwarz SMW200A vector signal generator configured with the SMW-B1006 frequency option (100 kHz to 6000 MHz) and the SMW-B10 standard baseband option. The VSG was tested to characterize the linear output power range and spectral purity in order to ensure that test waveforms contained energy only in the selected test frequency range.

The published specifications indicate that the output power setting range in the 3000 – 16000 MHz frequency band is -145 dBm to +30 dBm, while the specified level range is –120 dBm to +17 dBm peak

[15] *See* R&S®FSV Signal and Spectrum Analyzer Data Sheet, Version 13.00, Rohde & Schwarz, May 2019. Available at https://scdn.rohde-schwarz.com/ur/pws/dl_downloads/dl_common_library/dl_brochures_and_datasheets/pdf_1/FSV_FL_dat-sw_en_3606-7982-22_v1300.pdf.

envelope power (PEP).[16] The specifications provide a plot of the measured maximum available output level versus frequency for the SMW-B1006 frequency option, which indicates a maximum output of approximately +25 to +26 dBm PEP. 5G NR signals typically have a crest factor of 10-12 dB, which suggests that output compression should occur around +13 to +16 dBm.

The AVSI SMW200A instrument was characterized by measuring the channel power (Tx1) for a 100 MHz TM1.1 signal at each of the three center frequencies for various commanded output powers. The adjacent channel power (ACP) in the 100 MHz channels on either side of the Tx1 channel was also recorded. Figure 2-5 summarizes the results of these measurements.

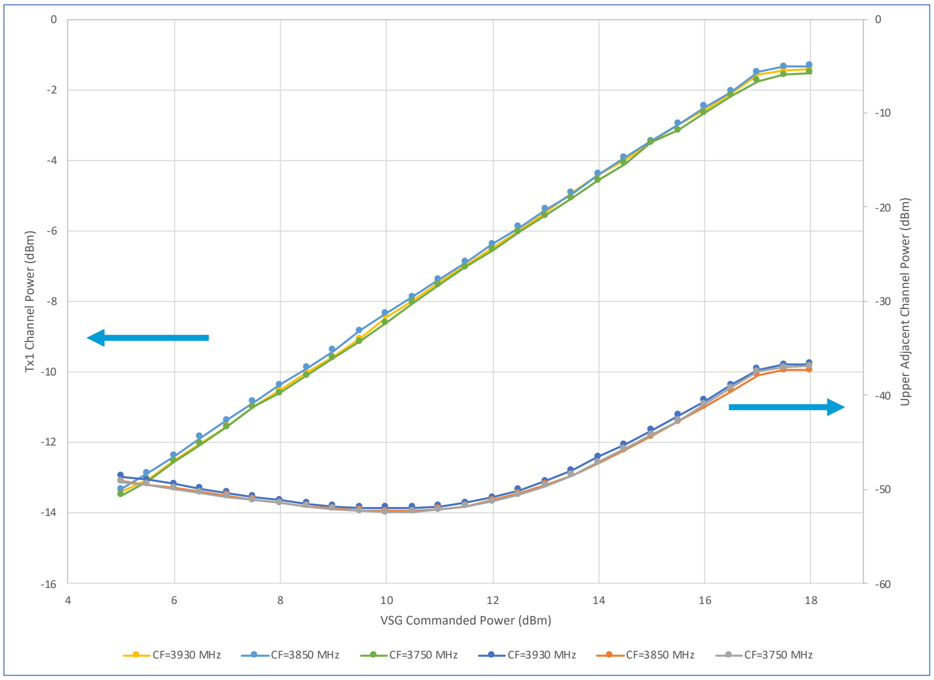
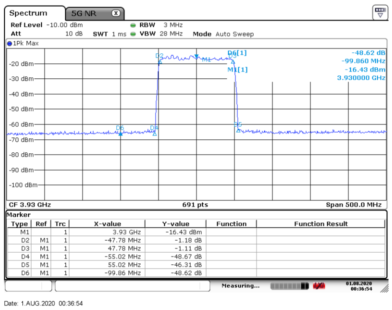


Figure 2-5: VSG Output Saturation

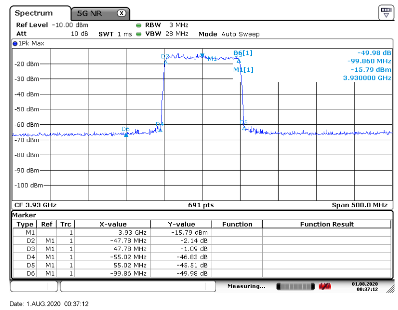
Figure 2-5 shows that the Tx1 channel output power is linear with respect to the commanded power up to at least +16 dBm, at which point the output is compressed and further increase in commanded power does increase power delivered to the AUT Rx input. The upper ACP does not change monotonically, but shows similar compression around +17 dBm.

These observations lead to characterization of the spectral purity of the VSG output to ensure that high commanded output powers do not introduce spectral components from the 5G emission into the 4200 – 4400 MHz band due to saturation of the VSG output. The upper ACP initially decreases until it reaches a minimum at +10 dBm commanded power, at which point the ACP rises until it reaches the output saturation point. This transition can be seen in spectrum analyzer screen shots shown in Figure 2-6.

[16] *See* R&S®SMW200A Vector Signal Generator Specifications, Version 15.00, Rohde & Schwarz, May 2021. Available at https://scdn.rohde-schwarz.com/ur/pws/dl_downloads/dl_common_library/dl_brochures_and_datasheets/pdf_1/SMW200A_dat-sw_en_3606-8037-22_v1500.pdf.



(a)



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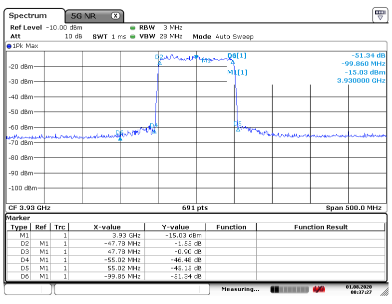
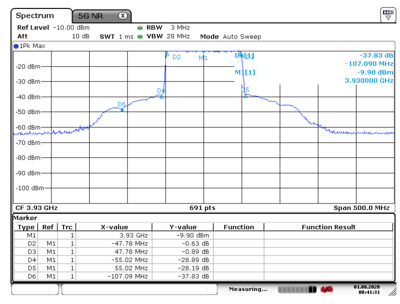


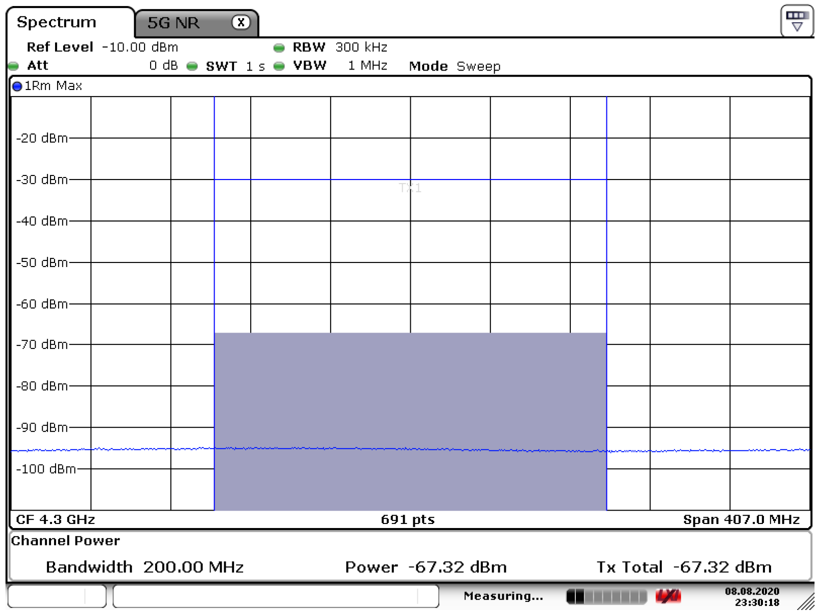
(c)



(d)

Figure 2-6: Spectrum Analyzer Screen Shots for Four VSG Output Power Settings (a) +8 dBm, (b) +9 dBm, (c) +10 dBm, and (d) +15 dBm for 100 MHz TM1.1 waveform centered at 3930 MHz (no band-stop filter)

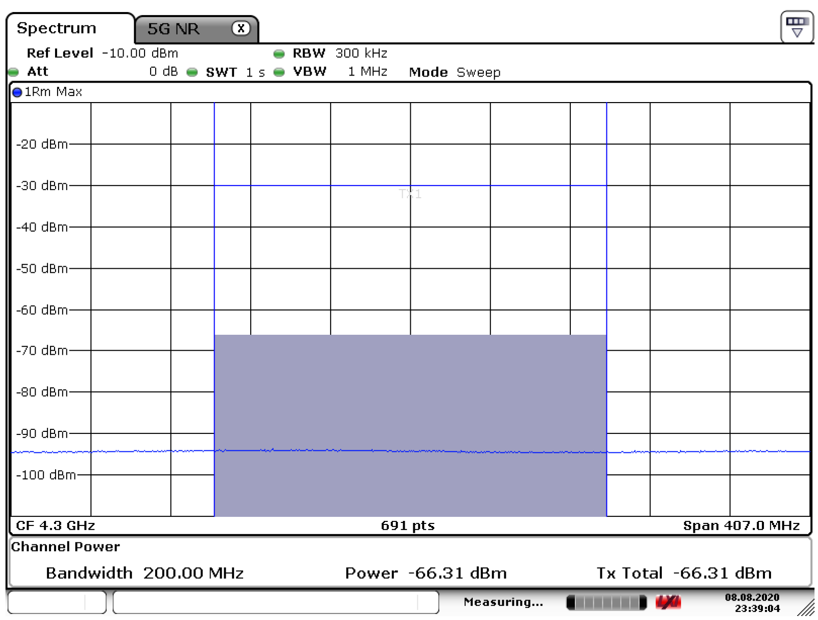
While the SMW200A specifies a maximum wideband noise of less than -150 dBc in the frequency range 200 – 6000 MHz, the VSG spurious output was measured to ensure that 5G fundamental emissions would not cause spurious RF energy in the 4200 – 4400 MHz frequency band. This was accomplished by utilizing the FSV7 spectrum analyzer to take several channel power measurements throughout the 4200 – 4400 MHz frequency band while the VSG was configured for the 5G fundamental emissions NR-FR1-TM 1.1 waveform in the 3700 – 3980 MHz band. To maximize the measurement sensitivity, these measurements were taken with the RF port normally connected to the radar altimeter receiver input and without the band-stop filter in place. At low VSG output power levels, the spurious levels in the 4200 – 4400 MHz band were below the spectrum analyzer's noise floor, which was determined to be -90 dBm/MHz based on a measured channel power of -67 dBm across the 200 MHz bandwidth. This is shown in Figure 2-7.



Date: 8.AUG.2020 23:30:19

Figure 2-7: Spurious Channel Power Measurement with Low VSG Output Power

In the 4200 – 4400 MHz band, increasing levels of VSG output power were tested until the measured channel power increased by 1 dB above the spectrum analyzer noise floor, equivalent to an average spurious level of -89 dBm/MHz. The measurement is displayed in Figure 2-8, and it occurred with a VSG output power of +5 dBm.



Date: 8.AUG.2020 23:39:05

Figure 2-8: Spurious Channel Power Measurement with +5 dBm VSG Output

Both the output saturation and 1 dB spurious power levels were well below the VSG output powers that set the interference power thresholds, thus these limitations on VSG output did not affect the AVSI testing. However, to ensure that no spurious energy from the VSG was in the 4200 – 4400 MHz band, a band-stop filter was used in the experimental apparatus for all 5G fundamental emission interference power threshold measurements. The filter response is shown in Figure 2-9, which illustrates the S21 parameter measured with a Rhode & Schwarz ZNB8 vector network analyzer between the vector signal generator output and the AUT Rx input. This illustrates that any VSG spurious content will be further attenuated by at least 25 dB. Therefore, the VSG spurious levels seen at the AUT Rx input during 5G fundamental interference testing would be no higher than -114 dBm/MHz with a VSG output of +5 dBm (and on average much less than this, as the band-stop filter provides more than 25 dB attenuation across most of the 4200 – 4400 MHz band). Further, it is anticipated that lower VSG output power settings would produce even lower spurious output levels than this limit.

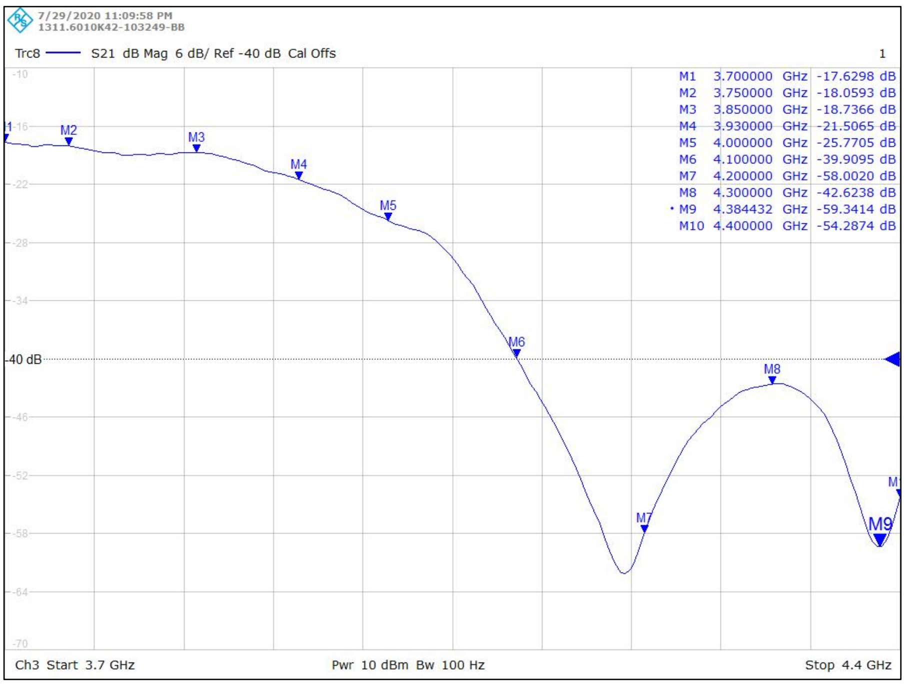


Figure 2-9: Band-stop Filter Frequency Response

2.2 Test Procedure

A single experiment, or “frequency sweep,” consisted of using the PC control computer to record all measured height readings reported on the standard output as the 5G interference power was stepped (“power sweep”) in 1 dBm increments (“power steps”) for each center frequency. Prior to running a frequency sweep, the AUT was turned on for a sufficient time to allow it to stabilize and experimental parameters (altimeter model, nominal height, modulation type, etc.) were recorded. All 5G fundamental emissions measurements were conducted with a 100 MHz NR-FR1-TM1.1 waveform at three center frequencies (3750, 3850, and 3930 MHz). As illustrated in Figure 2-10, each frequency sweep typically consisted of 4 distinct time periods that included an initial one minute baseline period, during which the 5G RF interference power was turned off while the RA operated normally to establish a baseline confirming proper operation of the AUT, and up to three power sweeps, one for each center frequency being tested (3750, 3850, and 3930 MHz).

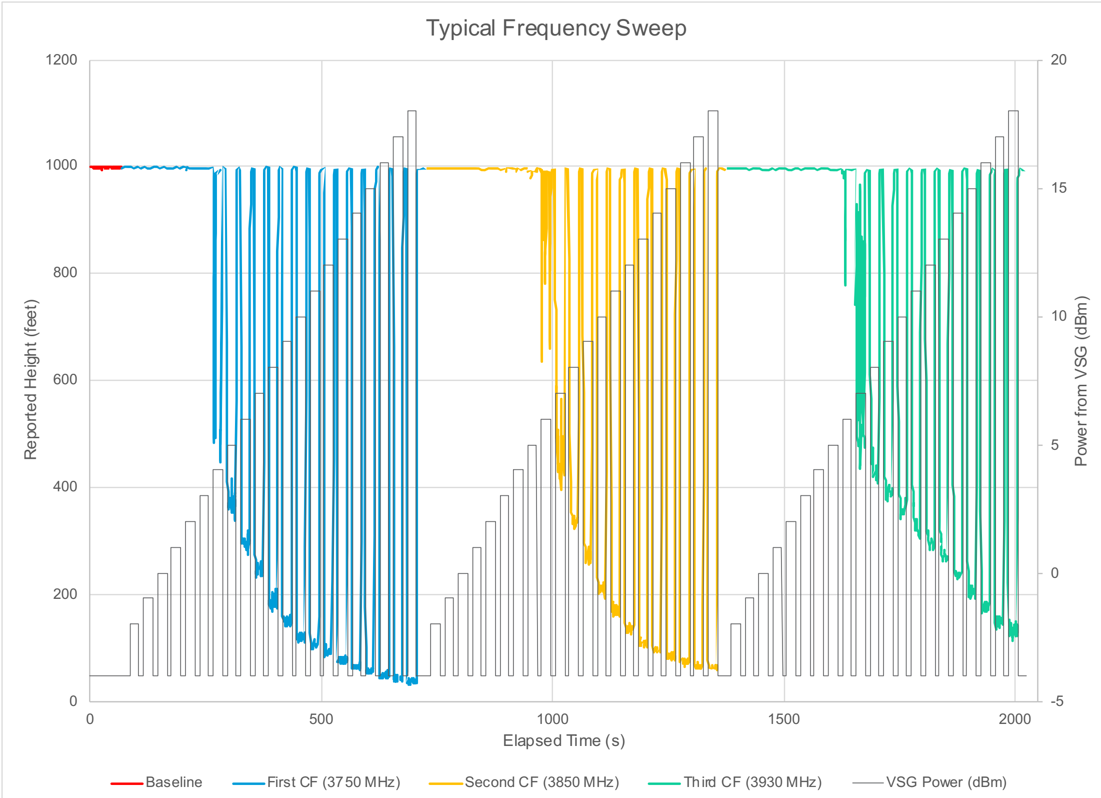


Figure 2-10: Typical Frequency Sweep

In cases where in-band FMCW interference signals were used (for own-ship interference and/or the WCLS), the VCOs used to generate the signals were powered on throughout the frequency sweep, including during the initial baseline period. After each change in center frequency, the AUT was allowed to settle for 30 seconds before starting a power sweep. The band-stop filter in the RF circuit was used for all measurements, as described in Section 2.1.3.2. All 5G spurious emissions measurements used a 160 MHz AWGN signal at a single center frequency of 4300 MHz. As described in Section 2.1.3.2, the band-stop filter was not used in the spurious emissions measurements.

Each power step in a power sweep included a 10 second period when the RF output was turned off at the VSG, followed by a 20 second period when the RF power at the VSG was turned back on, as illustrated in Figure 2-11. Ballard Co-Pilot software was used to record the measured height, which included an independent time stamp generated by the bus converter. The time-stamped interference signal settings were also recorded by the Python control software for each frequency sweep.

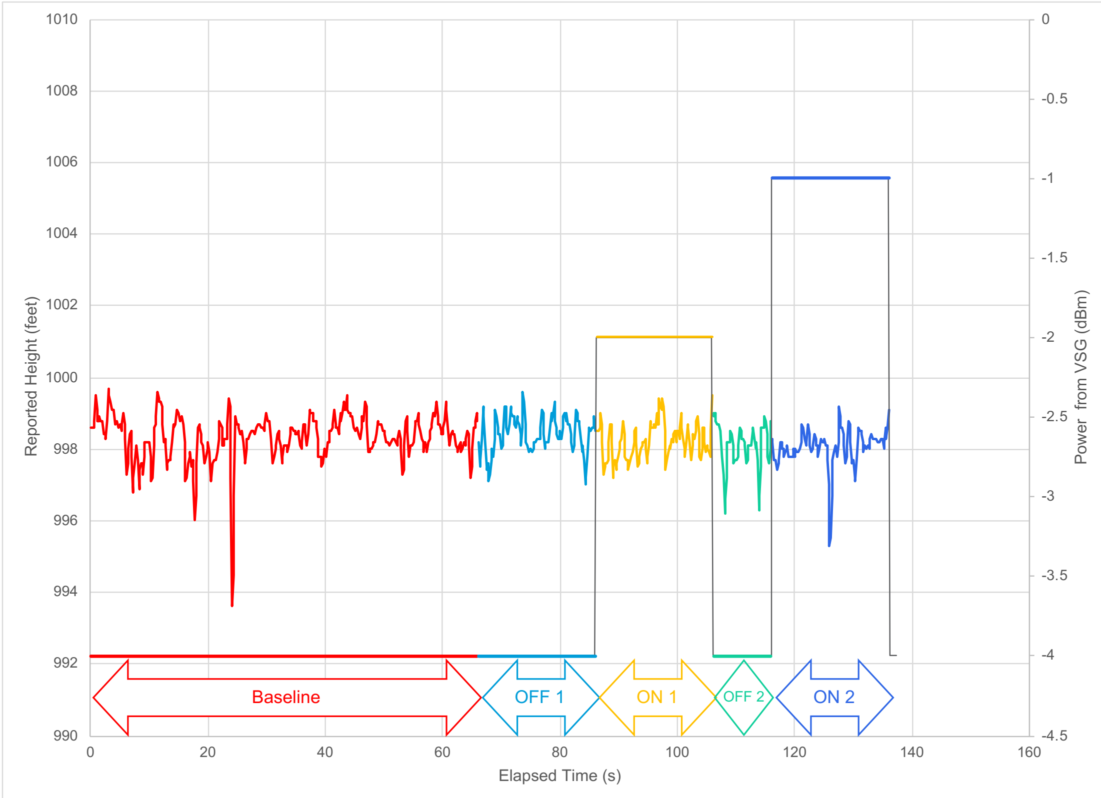


Figure 2-11: Power Sweep Intervals

2.3 Data Analysis and Representation

2.3.1 Database Files and Post-Processing

The data accumulated over the course of a frequency sweep was stored in two locations, a Structured Query Language (SQL) database that was generated by the Python control software and an Excel file exported from the CoPilot software containing the time stamped data reported by the AUT on the ARINC 429 bus (time resolved height data for Altimeter V was captured by the Python software and similarly stored in an Excel file). The database contained tables that stored the experimental parameters (AUT, nominal height, etc.) and the time stamped VSG control signals (commanded output power and RF ON/OFF state). The exported Excel file contained time stamped reported height and error messages.

Python scripts and libraries (numpy, scipy, pandas, etc.) were used to post-process the frequency sweep data. The primary functions of the post-processing software were to:

1. Merge the time history of the experimental control output with the data acquired by the CoPilot software. This included merging the time base from the ARINC 429 time stamps on the height data and the control computer internal clock time stamps on the control signal data. An output table was generated that contained a single time history of the reported height, VSG output power, NCD/error indication, and RF output state, which was stored in the same database.
2. Generate time history plots. As described below, the merged data was plotted on a time history plots that illustrate the reported height and interference power level at the RA Rx input on a single plot for each power sweep in a frequency sweep.

3. Generate statistical plots. As described below, statistical plots were generated for each power sweep to illustrate statistical parameters for the distribution of reported heights in each RF power ON period of each power step in a power sweep.

The time history plots and statistical plots were examined by the AFE 76s2 members to determine the RF interference power at which the behavior of the AUT became unacceptable. The Python software also generated threshold plots according to the criteria described in Section 2.3.4, but these automatically generated thresholds were confirmed by manual review of the time history and statistical plots.

2.3.2 Time History Plot

Figure 2-12 shows a typical time history plot generated during post-processing for a typical power sweep. The blue trace plots the measured height reported by the AUT in feet with values indicated on the primary (left) vertical axis. The green trace plots the 5G interference power at the Rx port of the AUT in dBm with values indicated on the secondary (right) vertical axis. This is computed from the time history data by subtracting the attenuation measured between the VSG output and the RA Rx input from the VSG output power, as described in Section 2.1.3.2. Note that the RF power OFF periods are shown as a nominal value offset from the minimum applied power for illustration only, since the secondary axis is logarithmic (dB). Data points for which the altimeter was unable to report a reliable measured height are shown as red dots along the blue trace.

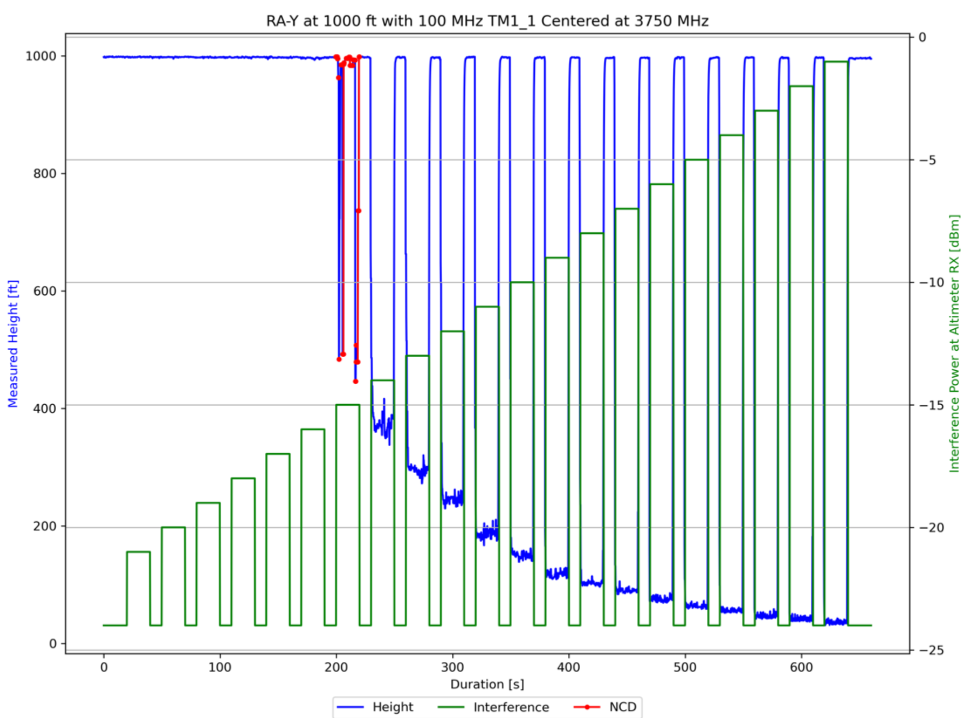


Figure 2-12: Typical Time History Plot

For altimeters that output data on the ARINC 429 bus, these unreliable measured height outputs include a status flag indicating No Computed Data (NCD). For Altimeter V, two discrete signals indicate validity and error conditions (equivalent to the NCD or Failure Warning status indications on the ARINC 429 bus for all other altimeters). Criteria for reporting NCD vary depending on the specific signal processing in different altimeters, but it is generally indicative of a condition in which the signal-to-noise ratio of the received signal is insufficient to compute an altitude with the required level of confidence.

Time history plots provide a view of the altimeter behavior over a full power sweep. They give a qualitative indication of how different levels of interference affect the performance, including noisiness of the reported height, frequency of NCDs, and the relative change in measured height for increasing levels of interference.

2.3.3 Statistical Plot

Statistical plots were generated by computing the statistics of the reported height for each RF interference power ON and power OFF interval for each power step in a power sweep, as illustrated in Figure 2-11. The parameters computed for the RF power ON interval of each power step included the minimum value, maximum value, mean, median, standard deviation, first percentile height, and ninety-ninth percentile height. These were then normalized to a percentage of the “undistorted height,” which was taken to be the mean of heights reported during the RF power OFF period of the same power step, excluding the first and last 1.75 seconds of that period to eliminate any transient effects in the computation of the mean. As for the time history plots secondary vertical axis, the horizontal axis of the statistical plots is the 5G interference power at the Rx port of the AUT in dBm.

Figure 2-13 shows a typical statistical plot, which in this case is based on the same data used to generate the time history plot in Figure 2-12. The traces in the statistical plots include (all values normalized as a percentage of the undistorted height):

- Blue trace: Mean measured height during the 5G RF power ON period for the indicated 5G interference power. A mean measured height during the 5G RF power ON period where no recorded measured height was flagged as NCD is plotted with a blue dot. A red X indicates that one or more recorded measured heights were flagged as NCD. Error bars for each point are plus and minus one standard deviation of the measured height for the given 5G RF power ON period.
- Black dash trace: The maximum measured height during the 5G RF power ON period.
- Black alternating dash dot trace: The minimum measured height during the 5G RF power ON period.
- Green dash trace: The cumulative distribution function (CDF) 99th-percentile of all measured heights during the 5G RF power ON period.
- Green alternating dash dot trace: The CDF 1st-percentile of all measured heights during the 5G RF power ON period.

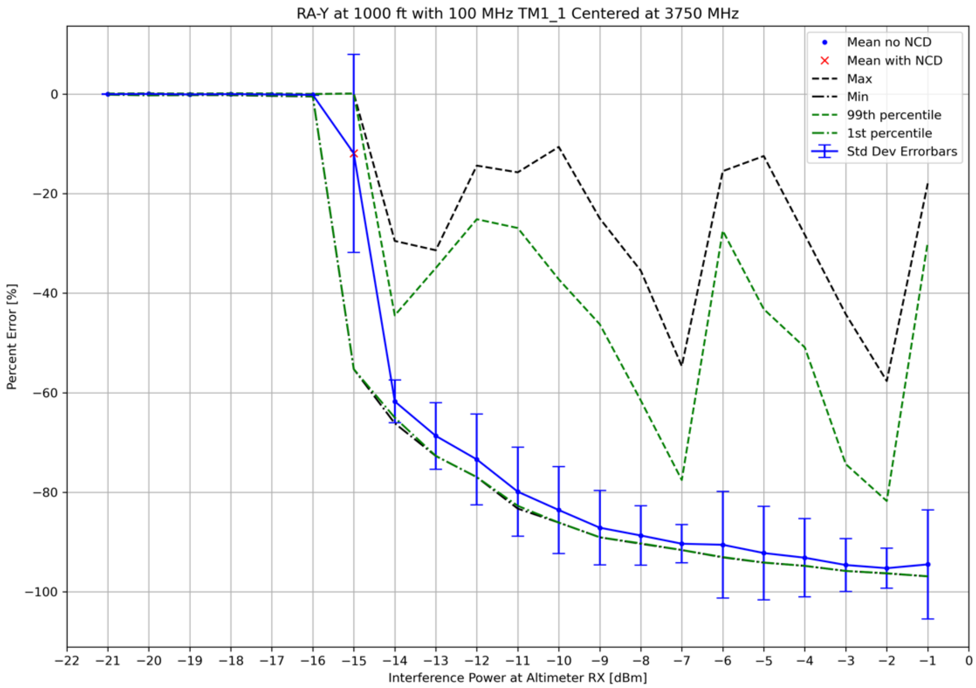


Figure 2-13: Typical Statistical Plot

Statistical plots were plotted in both a full and magnified vertical scale as necessary in order to verify the threshold criteria. For example, the plot shown in Figure 2-13 is the same full scale view shown in Figure 3-68, whereas Figure 3-69 illustrates the same data on a magnified scale.

2.3.4 Interference Tolerance Threshold Criteria

The intent of AVSI testing was to determine the effects of new 5G emissions on the performance of existing RAs. To this end, the testing captured measured heights with the out-of-band RF interference turned both on and off. The analysis then examined the difference between the statistical parameters in each case, thus isolating the changes caused by the simulated 5G emissions. These changes, plotted on the time history and statistical plots described above, typically show that the AUT is able to process the return signal in the presence of the static in-band and increasing out-of-band injected RF noise up until a point at which the out-of-band noise power exceeds a threshold, after which the height reported by the altimeter is noticeably affected, indicating that the altitude measurement has been compromised by the presence of 5G interference.

Interference tolerance threshold criteria were defined by the radar altimeter design engineers and aircraft systems experts on this project in order to provide a basis for determining the 5G interference power at which this threshold is crossed. These criteria considered three properties of the measured heights during each 5G RF power ON period: changes to the mean height, changes to the distribution of measured heights as reflected by the first and ninety-ninth percentile heights, and the occurrence of NCD or equivalent indications. The threshold was determined by identifying the lowest 5G interference power that caused any one criterion to be true.

2.3.4.1 Mean Error Criterion

As described above, the mean measured height was computed for each 5G RF power ON period and normalized as a percentage of the undistorted height to give a mean error. The mean error was observed for increasing levels of 5G interference power. The AUT was considered to “break” (i.e., the performance becomes unacceptable considering subject matter experts’ experience with the known performance requirements) when the mean error exceeds 0.5%, i.e.:

$$\frac{|Mean\ Height(5G\ RF\ on) - \ Mean\ Height(5G\ RF\ off)|}{Mean\ Height(5G\ RF\ off)} * 100\% > 0.5\%$$

This criterion considers the average performance of the altimeter in the presence of 5G interference during the 5G RF power ON period, which is indicative of the impact of the 5G interference on the absolute accuracy of the RA.

2.3.4.2 Percentile Criterion

Beyond changes to the average behavior, the time history plots often displayed increasing fluctuation in the measured height with increasing interference power and a broadening of the distribution of measured heights about the mean. This behavior was included in the determination of the break point by computing the cumulative distribution from a histogram of the measured heights and then determining the height for which 1% of all measured heights are less (1st percentile) and the height for which 99% of all measured heights are less (99th percentile).

The measured heights were typically not normally distributed about the mean. However, the subject matter experts on this project specified that the break point was that 5G interference power at which the interference induced broadening of the distribution caused fewer than 98% of all data points in the 5G RF power ON interval to fall within ±1.5 ft or ±2% (whichever is greater). On the statistical plots, this occurs when the 1st percentile trace drops below -2% or the 99th percentile trace exceeds +2%:

$$H_{1\%} < (Mean\ Height(5G\ RF\ off) - 2\%) \quad \text{or} \quad H_{99\%} > (Mean\ Height(5G\ RF\ off) + 2\%)$$

where $H_{1\%}$ and $H_{99\%}$ are the normalized 1st and 99th percentile heights.

2.3.4.3 No Computed Data (NCD)

An altimeter asserts a NCD indication when the signal processing is not able to reliably determine a measured height. This can be caused by anything that affects the signal-to-noise ratio of the desired return signal. It was determined by the experts on this project that one or more NCDs that occur during a 5G RF power ON period is indicative of a condition in the RA receiver that could prevent it from meeting its performance requirements. Thus, the criterion is that the lowest 5G interference power that produces any height reading label NCD during the RF power ON period is a break point.

2.3.4.4 Engineering Judgment

As described above, all thresholds were determined both by application of the criteria in the Python post-processing software and by subject matter expert review of the time history and statistical plots. Some test conditions produced time history and statistical plots for which the threshold was not as clearly defined as that illustrated in Figure 2-12 and Figure 2-13. In some of these cases, the engineering judgement of the subject matter experts identified a break point that was different than the computed break point. In most cases, this led to a break point that was at a higher 5G interference power than that computed by strict application of the threshold criteria. These cases are identified in the detailed data presented in Section 3.

2.3.4.5 Rationale for Interference Tolerance Threshold Criteria

The interference tolerance threshold criteria were created to provide an aide for evaluating changes to the behavior of the radar altimeters in the presence of in-band and out-of-band RF interference. While minimum performance standards and regulatory requirements informed the selection of these criteria, they were not intended to reflect specified accuracy requirements. However, the similarity of the threshold criteria to some specified accuracy requirements has led to confusion over the applicability of these requirements to the criteria.

All nine RA models tested by AVSI received FAA design approval under either TSO-C87 or TSO-C87a Functional Class A. This means that all models meet an *absolute* minimum equipment height output accuracy requirement of ±3 ft from 3 to 100 feet, ±3% from 100 to 500 feet, and ±5% above 500 feet.[17]

In addition, some RA manufacturers specify more stringent accuracy performance, for example, to comply with the ARINC 707-7 standard of ±1.5 feet or 2% (whichever is greater) at all heights.[18] All five UC1 RAs claim ARINC 707 compliance and some of the UC2/UC3 RAs also claim this more stringent accuracy performance.

With this background, the selection of the interference tolerance threshold criteria was justified as follows:

1. The TSO-C87 and TSO-C87a accuracy requirements were defined for a spectrum environment that did not envision high-powered 5G signals in the near band. Hence, there was no margin built into the TSO MPS for the new spectrum environment established by the Report and Order. The MPS accuracy requirements, as stated in the performance standard itself, must be met across all operating conditions. Therefore, a single environmental parameter -- in this case 5G interference – could not be allowed to consume the entire error budget. Consequently, the AVSI interference tolerance threshold criteria were chosen to be more stringent than the MPS requirements for the RAs being tested.

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[17] For RAs authorized to TSO-C87, the precision equipment height output accuracy requirements are ±3 ft from 3 to 100 feet, ±3% from 100 to 500 feet, and ±5% above 500 feet (see TSO-C87 at 6). TSO-C87a defines two separate functional classes, Class A and Class B, and explicitly assigns separate requirements from ED-30 to each one (see TSO-C87a Table 1 at 2). TSO-C87a Class A is assigned the requirements for ED-30 Category L and Category A1, and TSO-C87a Class B is assigned the requirements for ED-30 Category P and Category B (see ED-30 at 9 for Category L and Category P requirements, ED-30 at 10-11 for Category A1 requirements, ED-30 at 11-13 for Class B requirements). A RA manufacturer applying for TSO-C87a must specify either Functional Class A, Functional Class B, or both (in which case all of the most stringent requirements across the two classes apply; TSO-C87a Table 1 at 2 stating "Note: It is possible for a radio altimeter to meet both functional classes"). The equipment height output accuracy requirements associated with TSO-C87a Functional Class A are equivalent to the original TSO-C87 precision equipment height output accuracy requirements (see ED-30 Table 1 at 10).

[18] Aeronautical Radio, Inc., ARINC Characteristic 707-7, *Radio Altimeter* at 18 (last published April 2019). ARINC Characteristics are aerospace industry standards that "Define the form, fit, function, and interfaces of avionics and other airline electronic equipment. ARINC Characteristics indicate to prospective manufacturers of airline electronic equipment the considered and coordinated opinion of the airline technical community concerning the requisites of new equipment including standardized physical and electrical characteristics to foster interchangeability and competition." Id. at ii.

2. The interference tolerance threshold criteria were developed to determine the onset of harmful interference, not the point at which interference becomes so severe that it drives the radar altimeter performance outside the MPS accuracy requirements. Otherwise, the MPS accuracy requirements could not guarantee that aviation systems would meet integrity, availability, and continuity requirements for safety critical systems under all operating conditions.
3. The TSO MPS accuracy requirements are with respect to *absolute* height accuracy, which would require the test setup to include proper tuning of installation delays and calibration of delay lines, which are unique to each RA tested. Such a test setup would have required significant additional effort and expense. Consequently, the AVSI tests were based on *relative* height accuracy where the criteria measured the deflection of accuracy between the baseline operating condition and the operating condition with 5G interference included; i.e., the 0.5% and 2% values were based on how much change there was from the mean reported height rather than measuring the difference from an absolute height. Thus, it made sense to set tighter interference tolerance thresholds than the full accuracy specification to allow for other sources of absolute altitude error which would not be observed in the relative accuracy assessment.
4. While some of the UC2/UC3 RAs do not claim compliance with the ARINC 707 accuracy performance, using a single set of interference tolerance threshold criteria allowed for consistent comparison of results between RAs.

Regardless, as shown in Section 2.3.4.7, the selected interference tolerance threshold criteria had little-to-no effect on the final ITMs, and the same results (within 1 or 2 dB in most cases) would have been obtained had a less stringent interference tolerance threshold criteria been chosen (such as 3% or 5%) for the UC2/UC3 RAs that do not claim ARINC 707 performance.

2.3.4.6 Interference Tolerance Masks (ITMs)

The break points determined by applying the interference tolerance threshold criteria to the statistical plots as described above were converted to ITMs for each UC and center frequency tested. This was done by identifying the lowest break point for all RAs in a UC at each nominal height (200, 1000, and 5000 feet for UC1) that was tested. Again, these break point values identified the power of the 5G interference at the Rx input of the AUT at which the performance becomes unacceptable. Thus, the *tolerance point,* which is defined as the highest power for which performance is still acceptable, is simply 1 dB less than the break point for the power steps used in this testing (that is, the highest interference power level tested at which the AUT has not yet met any of the break point criteria).

To further define the interference tolerance levels applicable to all currently deployed altimeters in a given UC for the full range of operating conditions, the tolerance point was further adjusted to account for experimental uncertainties and unit sampling uncertainties. The subject matter experts agreed that 1 dB back from the tolerance point was necessary to account for the sources of experimental error. Furthermore, this project tested a single unit of each of the altimeter models that were provided in a laboratory environment at room temperature. The project did not have access to multiple units of the same model to establish the interference tolerance variance and was not able to perform tests with the AUT at different ambient temperatures across the full range specified by the RA manufacturer. The RA subject matter experts on the project recommended an additional 4 dB back off from the tolerance point based on their experience with their models' unit-to-unit and environmental performance variations to account for this uncertainty in the RA units. Some manufacturers reported a 6 dB variation in performance across units for the same model, and it was decided that 4 dB being applied to all test results was a reasonable number to account for all the different manufacturers' systems.[19] Thus, a total of 5 dB was subtracted from the tolerance point (or 6 dB from the break point) to account for these uncertainties when applying the interference tolerance threshold to all fielded RAs.

Finally, the interference tolerance level for each height was converted from absolute power at the RA Rx input (in dBm) to the power spectral density (PSD – in dBm/MHz) for the 100 MHz wide TM1.1 test waveform. The PSD values were plotted against height on a semi-log plot to produce the ITMs, as shown in the example in Figure 2-14(a).

2.3.4.7 Sensitivity of Threshold Criteria

The interference tolerance threshold criteria were applied as described above to provide interference tolerance data to RTCA for use in their analysis summarized in the RTCA MSG Report.[20] Comments arising from public review of the RTCA MSG Report has revealed a misunderstanding of both the source and perceived stringency of the selected thresholds, leading to the faulty belief that less stringent criteria could result in significant changes in the reported ITMs. However, analysis of the sensitivity of the ITMs to variations in the statistical parameters used to determine the break points demonstrates that the ITMs are in fact insensitive to the changes in the threshold criteria. This reflects that which is evident from inspection of most of the time history and statistical plots, namely, that RA performance rapidly degrades for all 5G interference levels above the threshold.

To determine the sensitivity of the threshold values AVSI provided to RTCA that were the basis of ITMs plotted in the RTCA MSG Report, break points were computed for all power sweeps for all RAs tested for different values of a single parameter. The other parameters were fixed at the value used to determine the thresholds in the RTCA MSG Report. Specifically:

- Mean Error Threshold: The threshold at which the Mean Error is considered unacceptable was varied from the 0.5% value used in the RTCA MSG Report to the other values shown in Table 2-6 to determine the effect of requiring a larger interference induced deviation of the mean to establish the break point. The CDF Cutoff Percentile and Percentile Threshold parameters were fixed at the values used in the RTCA MSG Report shown in Table 2-6.
- CDF Cutoff Percentile: The low and high CDF Cutoff Percentile values were varied from the 1% and 99% values used in the RTCA MSG Report to the other values shown in Table 2-6 to determine the effect of requiring more measured heights readings to contribute to the threshold exceedance. The Mean Error Threshold and Percentile Threshold parameters were kept at the values used in the RTCA MSG Report shown in Table 2-6.

[19] Subsequent testing outside of the U.S. has shown that this may have been optimistic, with two different pulsed radar altimeter units of the same model showing up to 10 dB difference for bench testing RF interference susceptibility, without accounting for environmental changes. *See* ICAO FSMP, Working Group 12, IP/07 - Interference Susceptibility Evaluations of Pulsed Radio Altimeters Due to 5G Mobile Base Station Signal (dated 4 Oct 2021). Available at https://www.icao.int/safety/FSMP/MeetingDocs/FSMP%20WG12/IP/FSMP-WG12-IP07_Interference%20Susceptibility%20Evaluations%20of%20Pulsed%20Radio%20Altimeters%20Due%20to%205G%20Mobile%20Base%20Station%20Signal_rev1.pptx.

[20] The same interference tolerance thresholds were also used for the prior AVSI Preliminary Report and AVSI Supplemental Report filed in the same FCC Docket GN 18-122.

- Percentile Threshold: The Percentile Threshold value was varied to determine the effect of changing the threshold from the ± 2% values used in the RTCA MSG Report to other values shown in Table 2-6 to determine the effect of requiring a larger deviation of the 1st and 99th percentile heights from the mean to establish the break point. The Mean Error Threshold and CDF Cutoff Percentile parameters were kept at the values used in the RTCA MSG Report shown in Table 2-6.

Table 2-6: Threshold Criteria Sensitivity Study Values

Criterion	RTCA Report Threshold Value	Study Values				
Mean Error Threshold	0.5%	0.5%	1%	3%	5%	7%
CDF Cutoff Percentiles	1% / 99%	1% / 99%	2% / 98%	3% / 97%	4% / 96%	5% / 95%
Percentile Threshold	± 2%	± 2%	± 3%	± 5%	± 7%	-

The results include only the break points determined by either Mean Error or Percentile Criteria, as NCDs are not affected by the variation in the statistical parameters.

Table 2-7, Table 2-8, and Table 2-9 summarize the effect of changing the Mean Error Threshold, CDF Cutoff Percentile, and Percentile Threshold, respectively. Note that these tables show only changes for the specific criterion and do not consider changes in ITM values based on a change of the break point criterion, since only one parameter was varied at a time. For example, this analysis does not consider a case where varying the Mean Error threshold might drive the lowest power break point from a > 0.5% Mean Error criterion to a 1st Percentile < -2% criterion. Note also that these tables report only computed thresholds and do not apply engineering judgement to adjust the thresholds as was done for the values included in the RTCA MSG Report. However, the tables generally illustrate that all computed thresholds for the studied values are very close to the reported ITM values (that were not subject to engineering judgment).

Table 2-7: Effect of Changing Mean Error Threshold

Usage Category	Tested Height (ft)	Center Freq. (MHz)	Altimeter	Reported Threshold (dBm)	Computed Thresholds (dBm)				
					0.5%	1%	3%	5%	7%
UC1	5000	3750	F	-27	-26.8	-25.8	-24.8	-24.8	-24.8
		3850	F	-28	-29.3	-27.3	-27.3	-27.3	-27.3
		3930	F	-30	-31.0	-29.0	-28.0	-28.0	-28.0
UC2	200	3750	V	-50*	-59.8	-49.8	-49.8	-49.8	-49.8
		3930	V	-42*	-65.0	-65.0	-65.0	-65.0	-65.0
UC3	200	3750	V	-42*	-45.8	-41.8	-41.8	-41.8	-41.8
		3850	V	-38*	-39.3	-34.3	-34.3	-34.3	-34.3
		3930	V	-37*	-65.0	-65.0	-65.0	-65.0	-65.0

* – Indicates engineering judgement was applied to determine break point

Table 2-8: Effect of Changing the CDF Cutoff Percentile

Usage Category	Tested Height (ft)	Center Freq. (MHz)	Altimeter	Reported Threshold (dBm)	Computed Thresholds (dBm)				
					1%	2%	3%	4%	5%
UC1	200	3750	F	-13	-13.8	-13.8	-13.8	-13.8	-13.8
		3850	F	-15	-15.3	-15.3	-15.3	-15.3	-15.3
		3930	F	-16	-16.0	-16.0	-16.0	-16.0	-16.0
	1000	3750	F	-20	-20.8	-20.8	-20.8	-20.8	-20.8
		3850	F	-21	-21.3	-21.3	-21.3	-21.3	-21.3
		3930	F	-24	-24.0	-23.0	-23.0	-23.0	-23.0

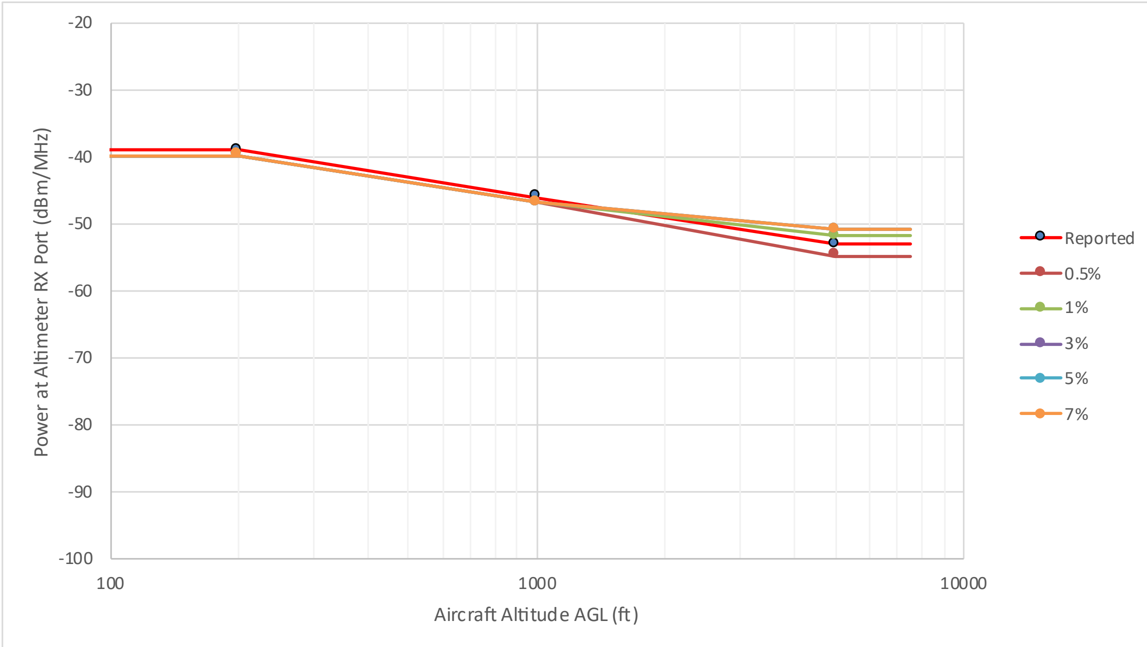
* – Indicates engineering judgement was applied to determine break point

Table 2-9: Effect of Changing the Percentile Threshold

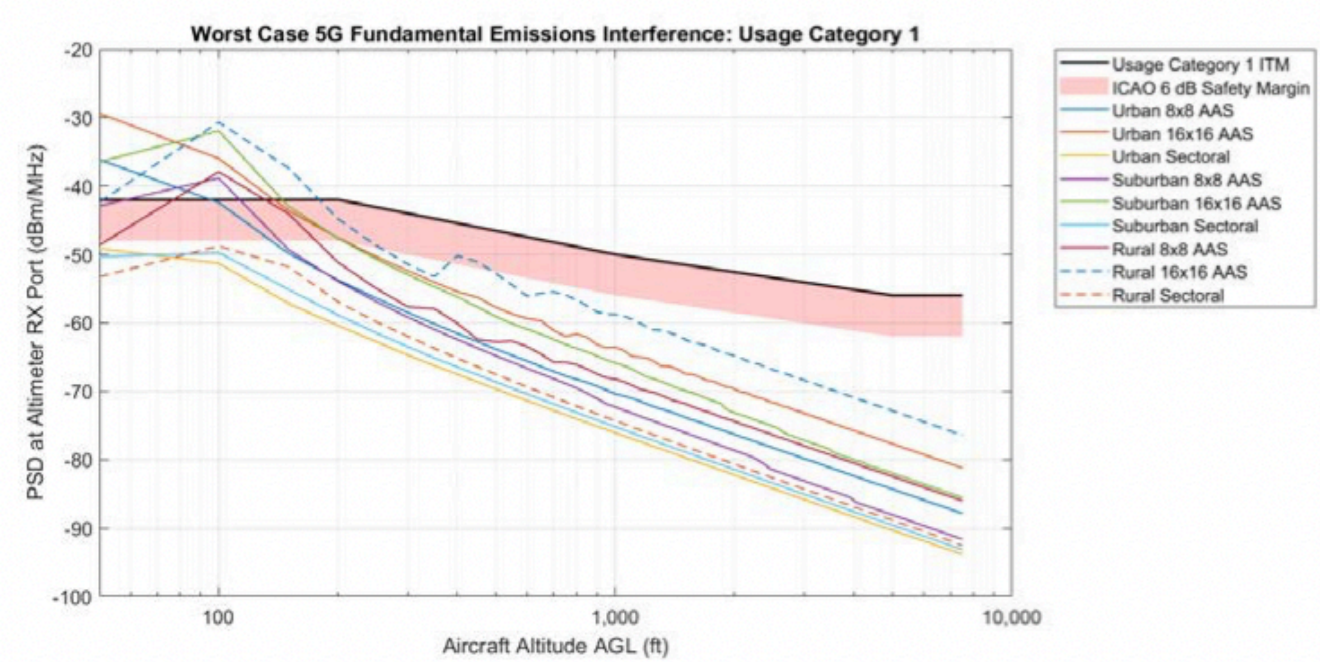
Usage Category	Tested Height (ft)	Center Freq. (MHz)	Altimeter	Reported Threshold (dBm)	Computed Thresholds (dBm)			
					2%	3%	4%	5%
UC1	200	3750	F	-13	-13.8	-13.8	-13.8	-13.8
		3850	F	-15	-15.3	-15.3	-15.3	-15.3
		3930	F	-16	-16.0	-16.0	-16.0	-16.0
	1000	3750	F	-20	-20.8	-20.8	-20.8	-20.8
		3850	F	-21	-21.3	-21.3	-21.3	-21.3
		3930	F	-24	-24.0	-23.0	-23.0	-23.0

* – Indicates engineering judgement was applied to determine break point

These tables indicate that since changes in the break point value are negligible, the ITM values reported in the RTCA MSG Report are insensitive to changes in the threshold criteria values. Again, this confirms what can be observed in the time history and statistical plots. Furthermore, any changes to the ITMs would not appear to materially affect the computed exceedances of the 5G signals reported in the RTCA MSG Report, as is illustrated in Figure 2-14 for the UC1 3750 MHz ITM. While this analysis did not consider the case of all thresholds set to the least stringent values at the same time, the negligible changes of the individual results indicate that this would not change the conclusions of the RTCA MSG Report.



(a)



(b)

Figure 2-14: Comparison of Threshold Changes to Reported Exceedances
(a) UC1 ITM for 5G fundamental emission at 3750 MHz for different mean error threshold values (in %)
(b) Maximum UC1 5G fundamental emissions levels for all center frequencies
(from RTCA MSG Report Figure D-3)

2.3.4.8 Break point Timing

The time history plots show the time dependence of 5G RF interference induced changes from the baseline behavior. Figure 2-15 shows a zoomed in view of the data shown in Figure 2-12. The transition from 5G RF power OFF to power ON at 230 seconds shows a typical decay from undistorted to distorted height. The power OFF period between 220 seconds and 230 seconds display a steady height very close to the nominal height of 1000 feet. The reported height readings drop to less than 400 feet when the 5G RF interference power is switched on at 230 seconds, but stays roughly at that level throughout the interval. The measured height returns to nominal when the 5G RF interference is switched off around 250 seconds, however it appears to do so just prior to the change in RF power illustrated by the green trace. This is due to a small amount of offset in the independent time stamp generated by the ARINC interface unit and the control computer clock, which was removed from the baseline height calculation by using a windowed subinterval as described above.

NCDs appear immediately after applying the 5G RF interference power in the 200 – 220 second power ON interval. The time to failure within a given power sweep / power step RF ON interval varied for different power sweeps, though Figure 2-15 shows that NCDs can occur at any point in the power sweep. The mean error and percentile threshold criteria are determined by *average* behavior of the measured height during the RF power ON interval of a power step; thus, it is not possible to time resolve the onset of those criteria within any given power step. However, the figure also shows that erroneous height readings appear immediately after the 5G RF interference power is applied at 230 seconds and again at 260 seconds. Thus, the dwell times selected (10 seconds RF OFF / 20 seconds RF ON) are sufficient to determine the break points caused by the introduction of 5G RF interference.

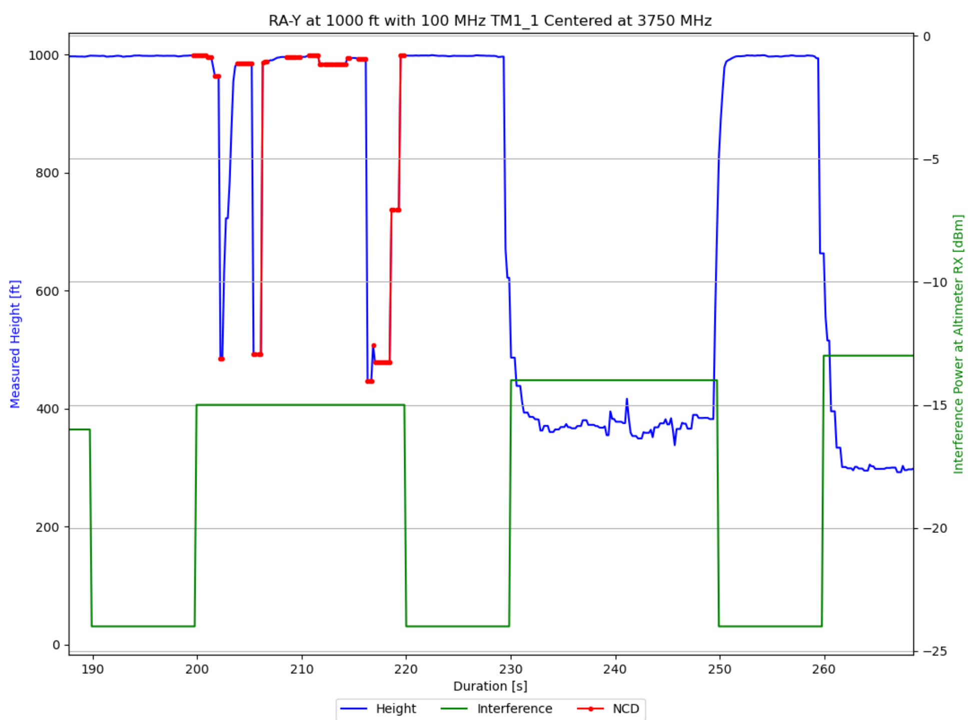


Figure 2-15: Time History Plot from Figure 2-12 with Expanded Time Scale

The timing of NCD occurrence within power steps was examined by collecting all power sweeps that exhibited NCDs and then computing the elapsed time within a power step that the NCD occurred. This was done separately for each RF interference power OFF and power ON interval of each power step. That is, for the time intervals illustrated in Figure 2-11, $0 \leq t_{OFF,i} < T_{OFF,i}$ and $0 \leq t_{ON,i} < T_{ON,i}$ for $i = 1..N$ power steps in a power sweep. The NCD messages were then tagged with the time of occurrence within their respective time intervals and the distribution of the time of occurrence was computed for all NCD occurrences in all power sweeps for all altimeters and test conditions. Figure 2-16 shows the number of NCD occurrences for each 0.5 second bin within the 20 second RF interference ON period for the 5G fundamental OOBI power sweeps for each center frequency (3750, 3850, and 3930 MHz). This shows that NCDs were fairly uniformly distributed.

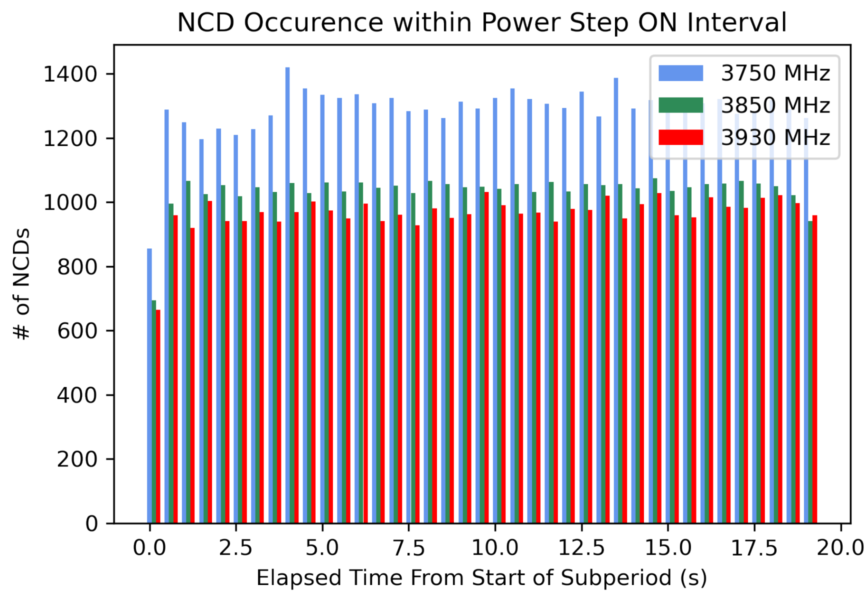


Figure 2-16: Distribution of NCD Occurrences in 5G Fundamental OOBI Power ON Interval

NCDs also occurred during the RF interference power OFF periods, but with much less frequency. There was a total of 130,846 NCDs for all 5G fundamental power sweeps during the RF OOBI power ON intervals, but only 9957 (7%) during the RF power OFF intervals. Figure 2-16 shows the number of NCD occurrences for each 0.5 second bin within the 10 second RF interference OFF period for the 5G fundamental OOBI power sweeps for each center frequency (3750, 3850, and 3930 MHz). This shows that the majority of NCDs occurred during an interference power OFF period register immediately after a transition from interference power ON to OFF. This suggests that the RAs have some recovery time, which is on the same order as the distortion onset time illustrated in Figure 2-15.

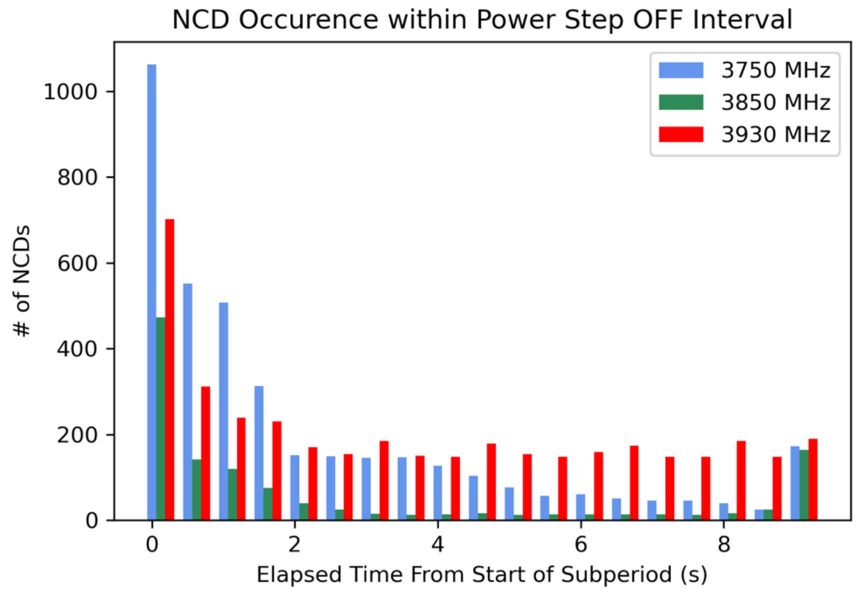


Figure 2-17: Distribution of NCD Occurrences in 5G Fundamental OOBI Power OFF Interval